US 20250251557A1

(19) **United States**

(12) **Patent Application Publication**

Yang et al.

(10) **Pub. No.: US 2025/0251557 A1**

(43) **Pub. Date: Aug. 7, 2025**

(54) **DETACHABLE OPTICAL FIBER-TO-WAVEGUIDE COUPLING**

(71) Applicant: **Applied Materials, Inc.**, Santa Clara, CA (US)

(72) Inventors: **Zijiao Yang**, Fremont, CA (US); **Jinxin Fu**, Santa Clara, CA (US); **Hans-Juergen Schmidtke**, Mountain View, CA (US); **Ludovic Godet**, Sunnyvale, CA (US)

(21) Appl. No.: **19/046,469**

(22) Filed: **Feb. 5, 2025**

Related U.S. Application Data

(60) Provisional application No. 63/704,096, filed on Oct. 7, 2024, provisional application No. 63/550,754, filed on Feb. 7, 2024.

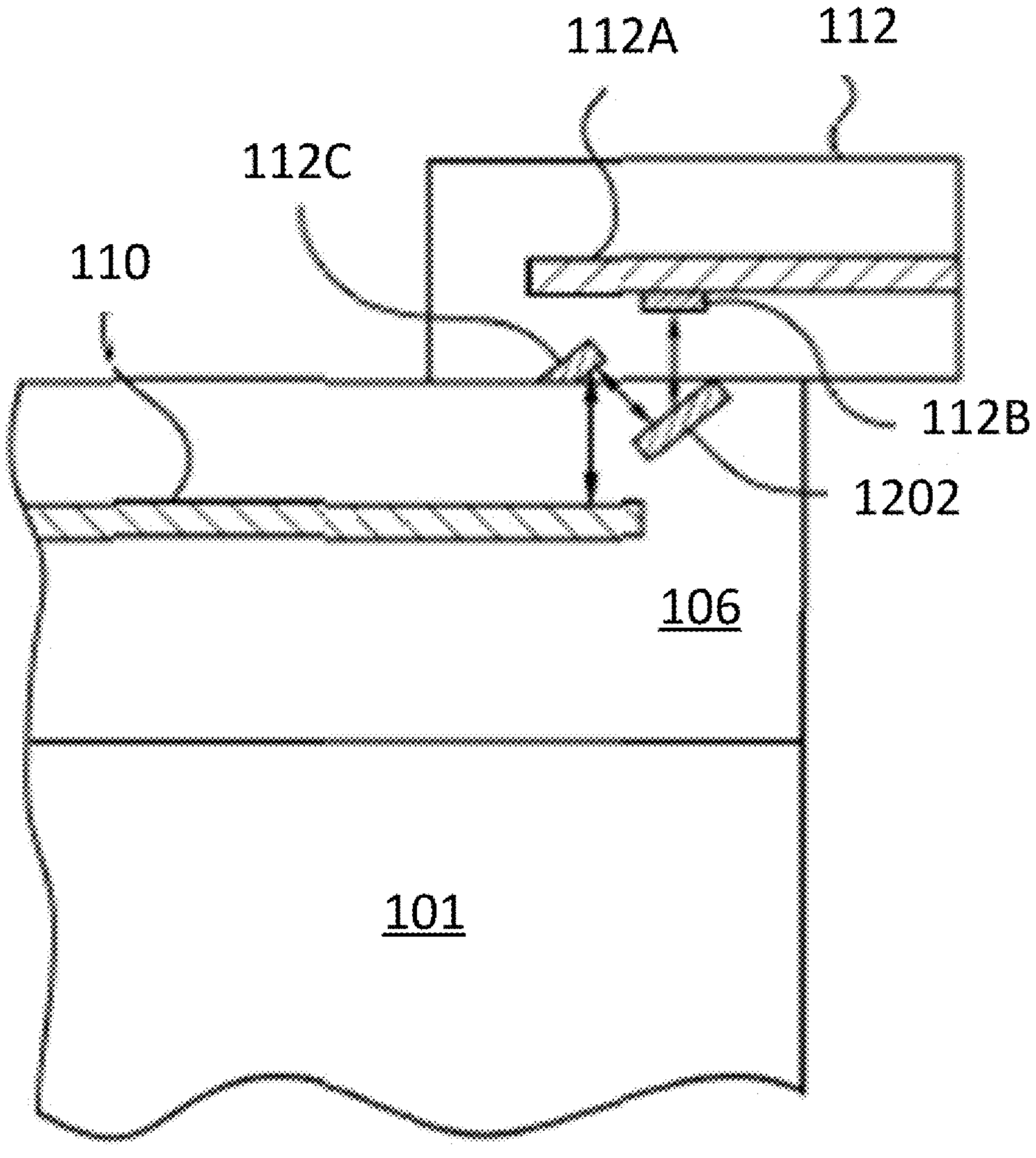
Publication Classification

(51) **Int. Cl.**
G02B 6/42 (2006.01)

(52) **U.S. Cl.**
CPC ***G02B 6/4292*** (2013.01); ***G02B 6/4214*** (2013.01)

(57) **ABSTRACT**

Embodiments described herein are related to enabling detachable optical fiber-to-waveguide coupling. A system can include a first connection component including a waveguide and a mirror formed on a base structure, the base structure including at least one photonic integrated circuit (PIC) formed on a substrate, and a detachable second connection component coupled to an optical fiber. The detachable second connection component is configured to mate with the first connection component to enable optical signal coupling between the optical fiber and the waveguide. The mirror is configured to at least one of: reflect a first optical signal received from the waveguide to the optical fiber, or reflect a second optical signal received from the optical fiber to the waveguide.



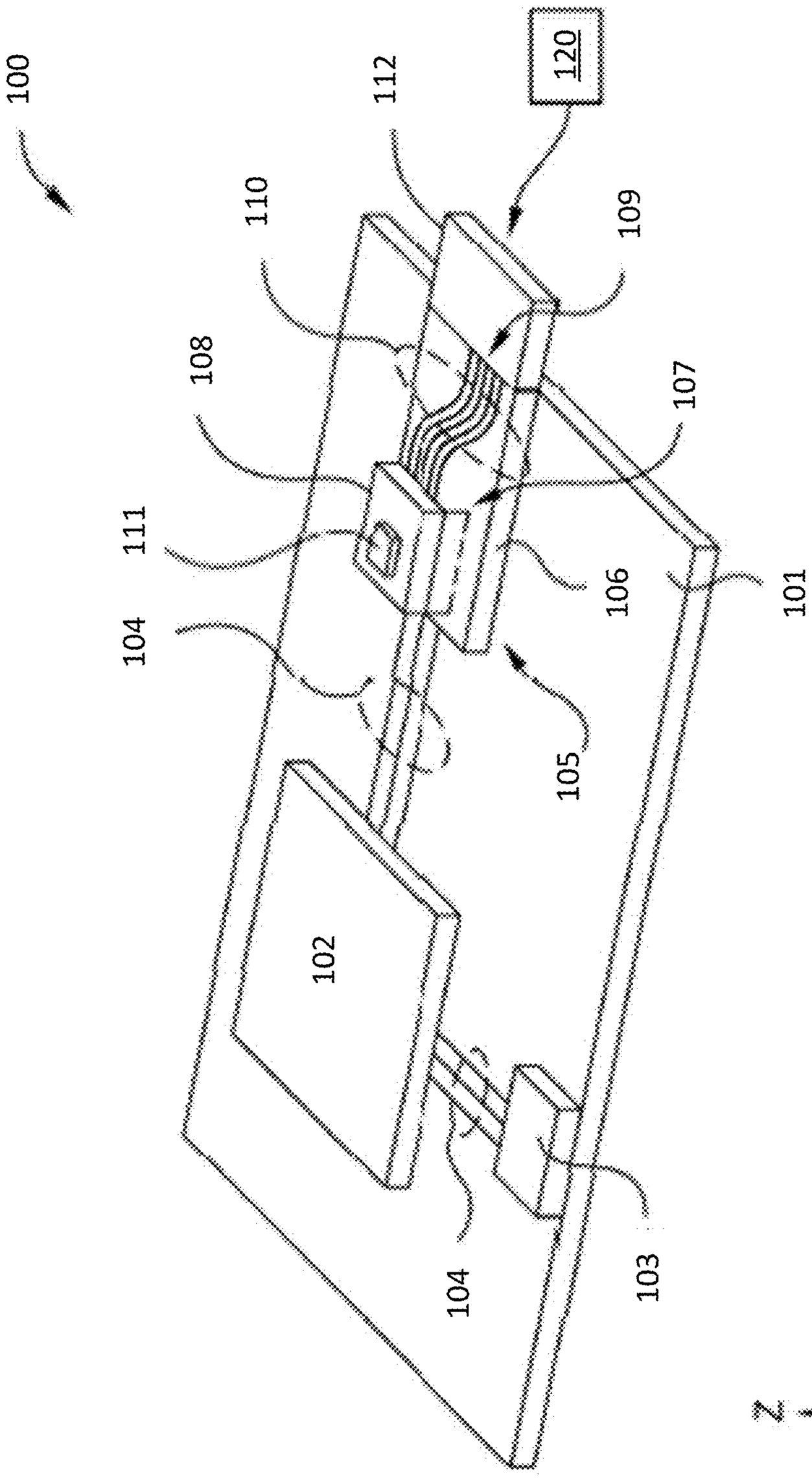


FIG. 1

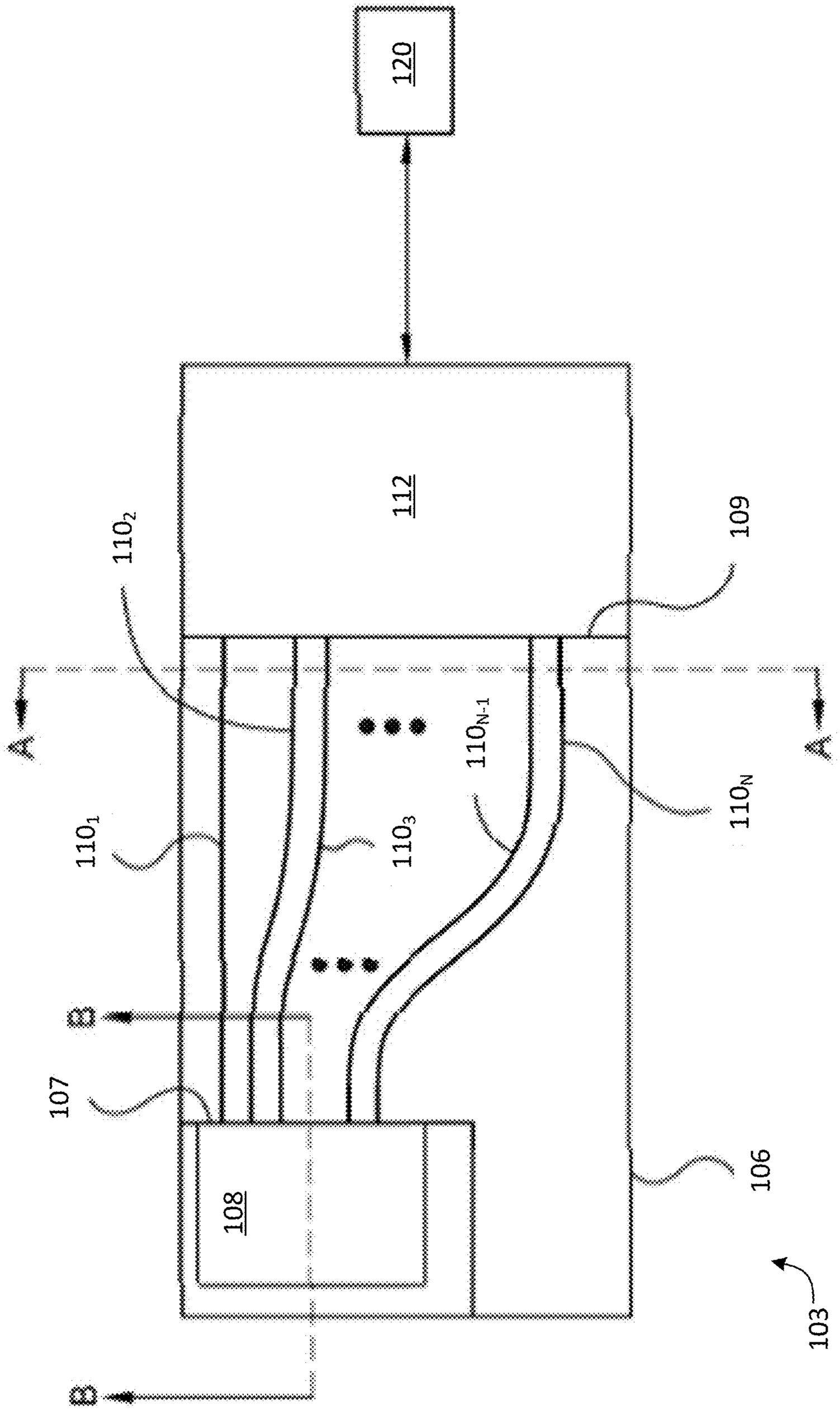


FIG. 2A

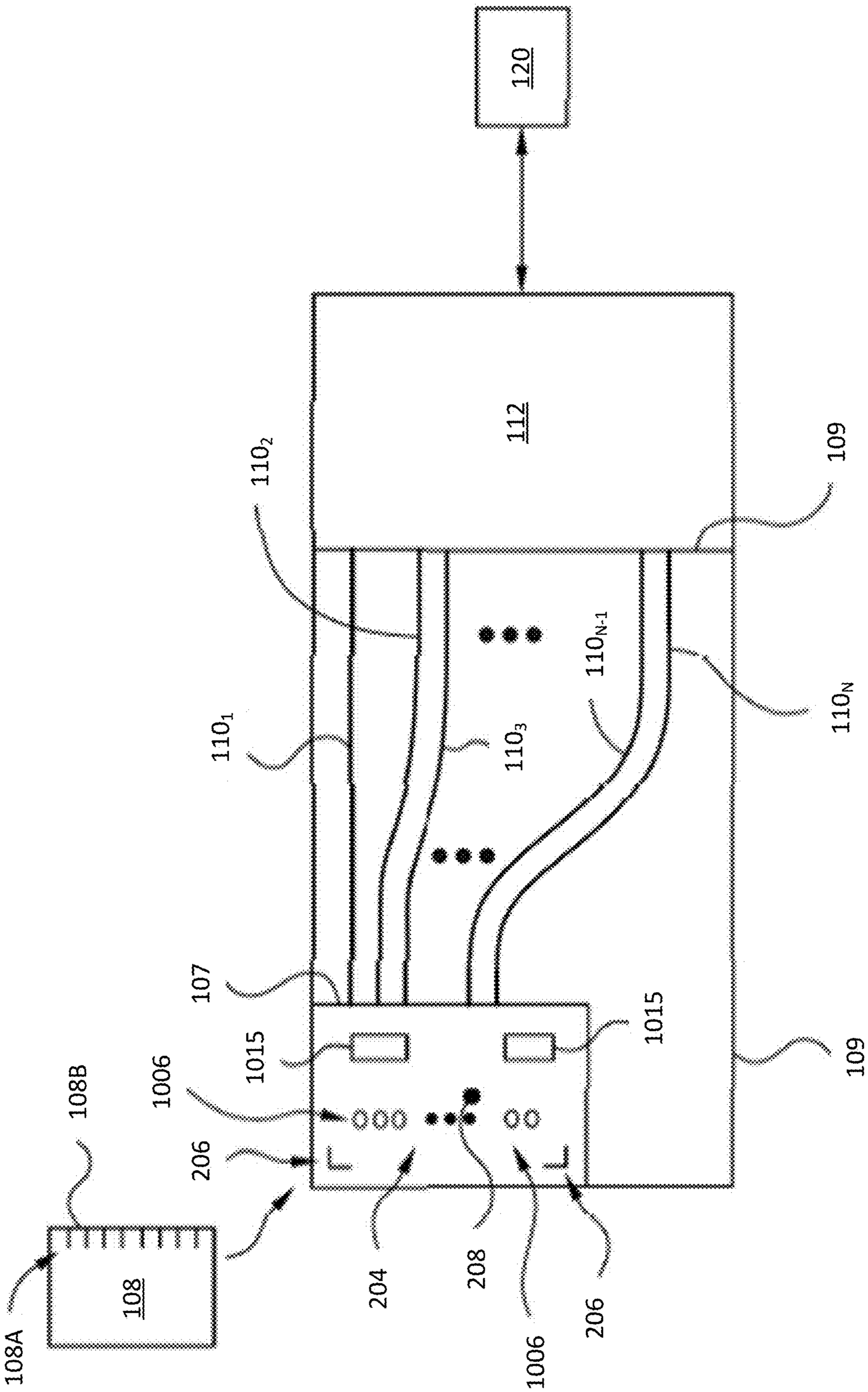

120
112
110_1
110_2
110_3
110_{N-1}
110_N
107
109
1015
1006
108B
108
108A
206
204
208

FIG. 2B

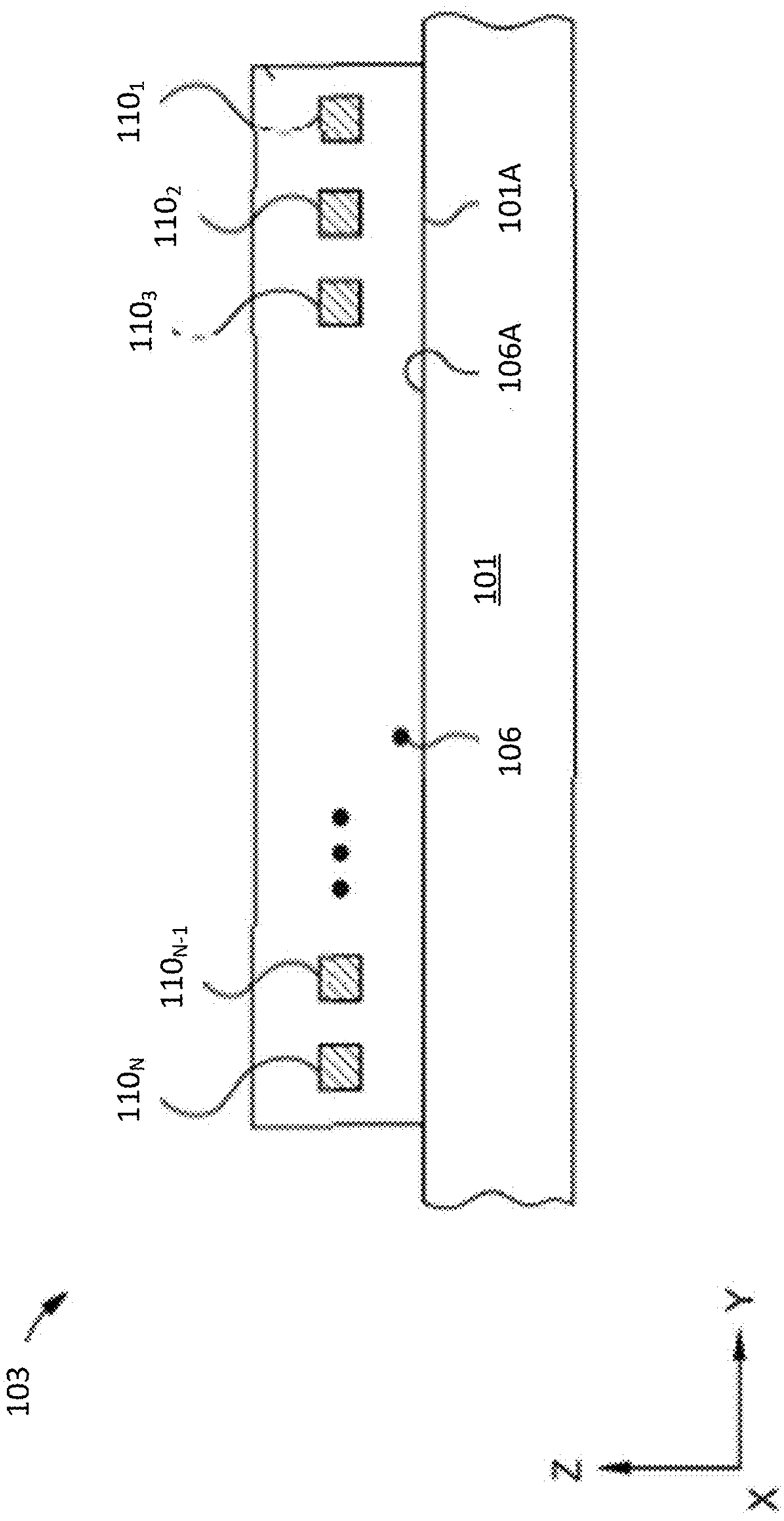


FIG. 3

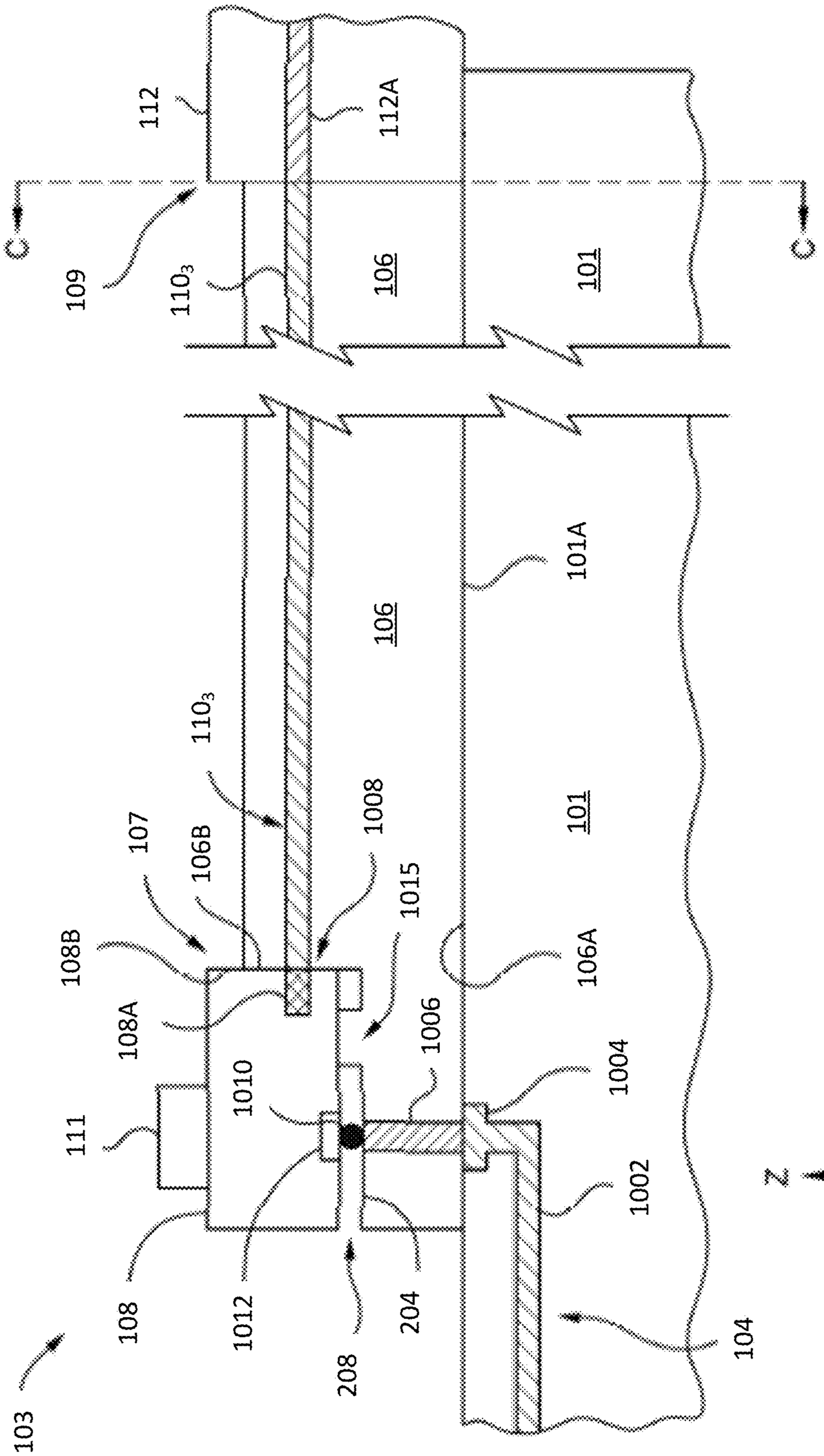

112
112A
109
110_3
106
101
103
108
108A
108B
107
106B
1008
1015
1006
1010
1012
208
204
111
106A
101A
1004
1002
104
Z
Y
X

FIG. 4

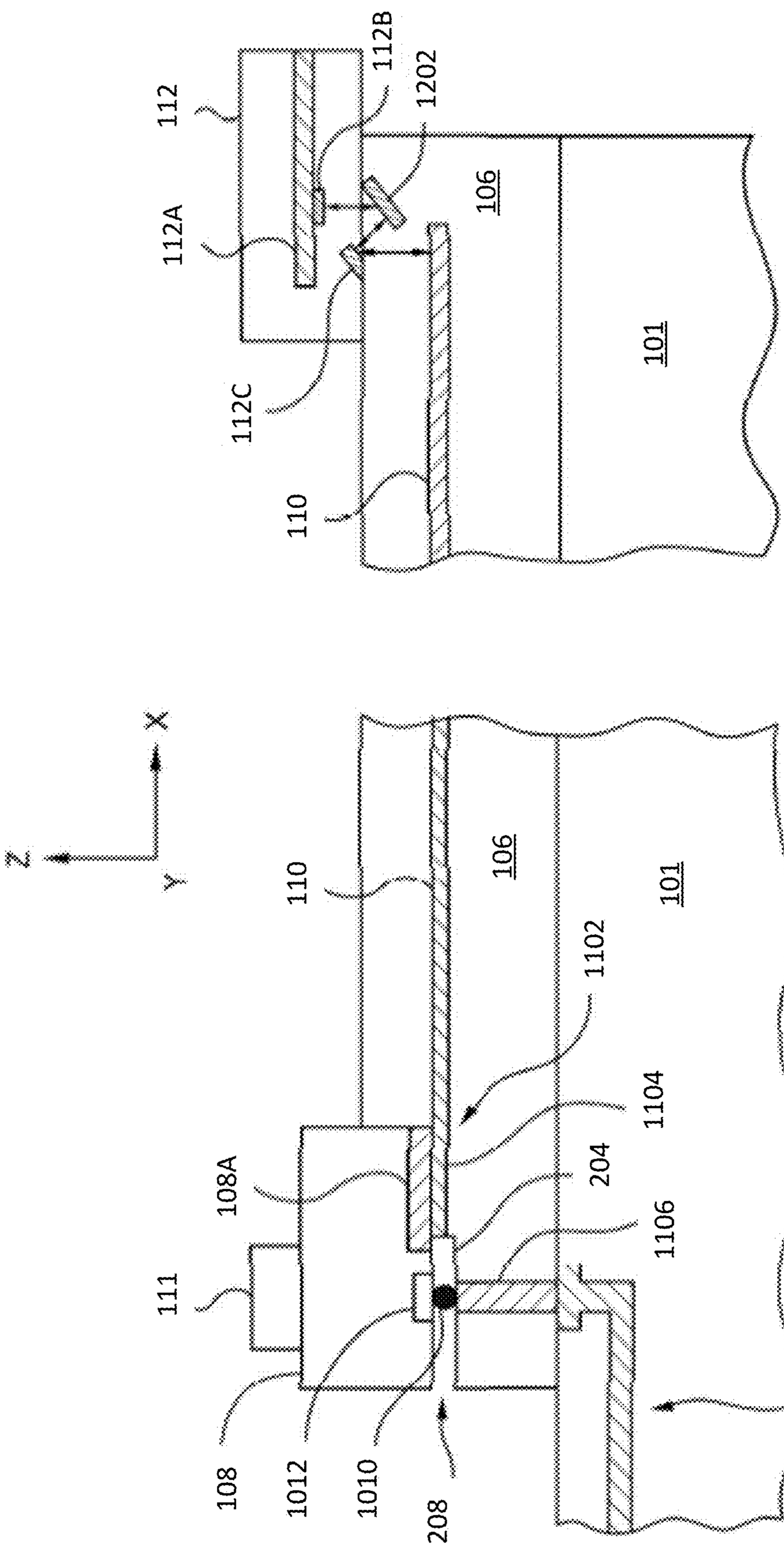

112
112B
1202
112A
106
101
112C
110
110
106
1102
101
Z
X
Y
111
108A
204
1104
1106
108
1012
1010
208
104

FIG. 6

FIG. 5

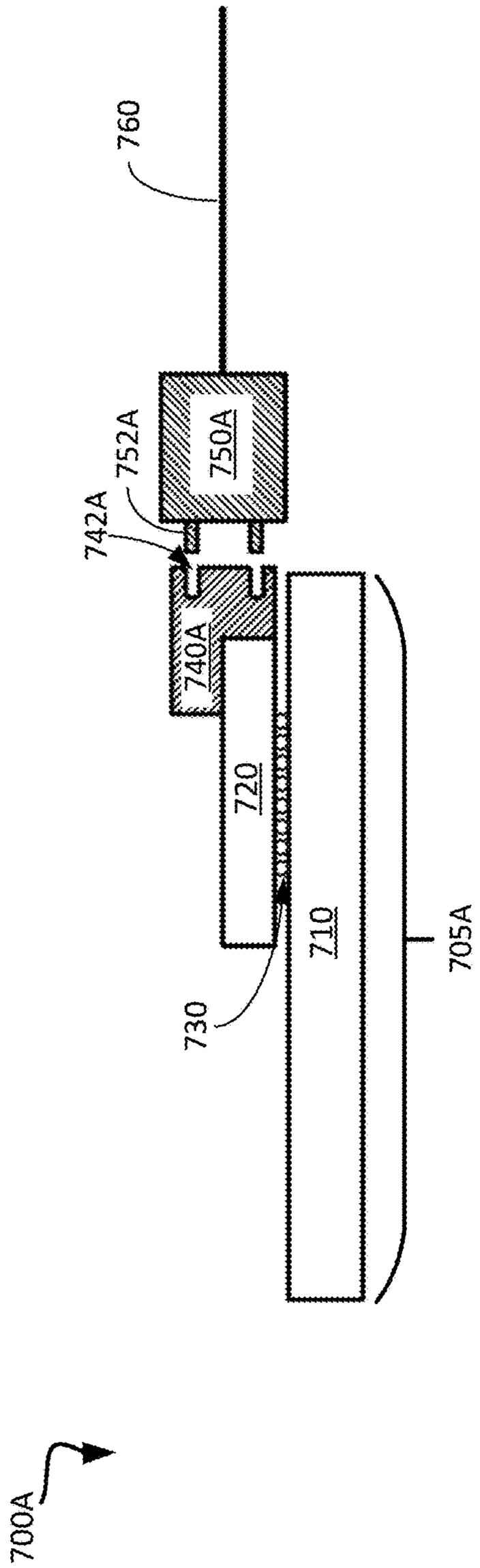

760
752A
750A
742A
740A
720
730
710
705A
700A

FIG. 7A

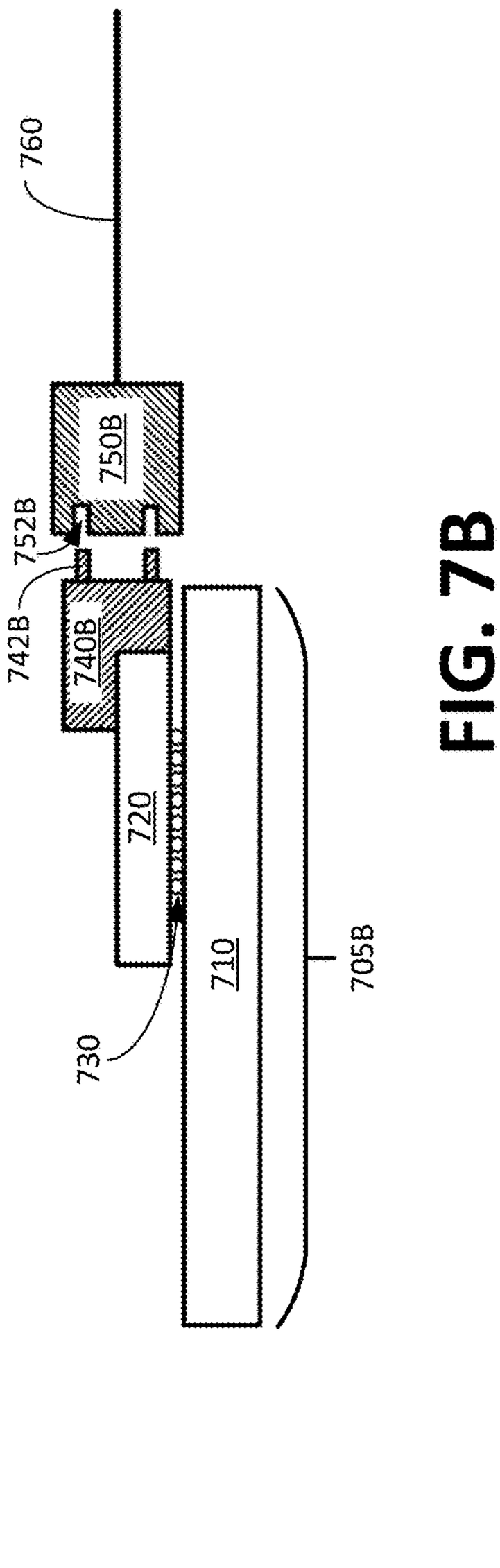

760
752B
750B
742B
740B
720
730
710
705B
700B

FIG. 7B

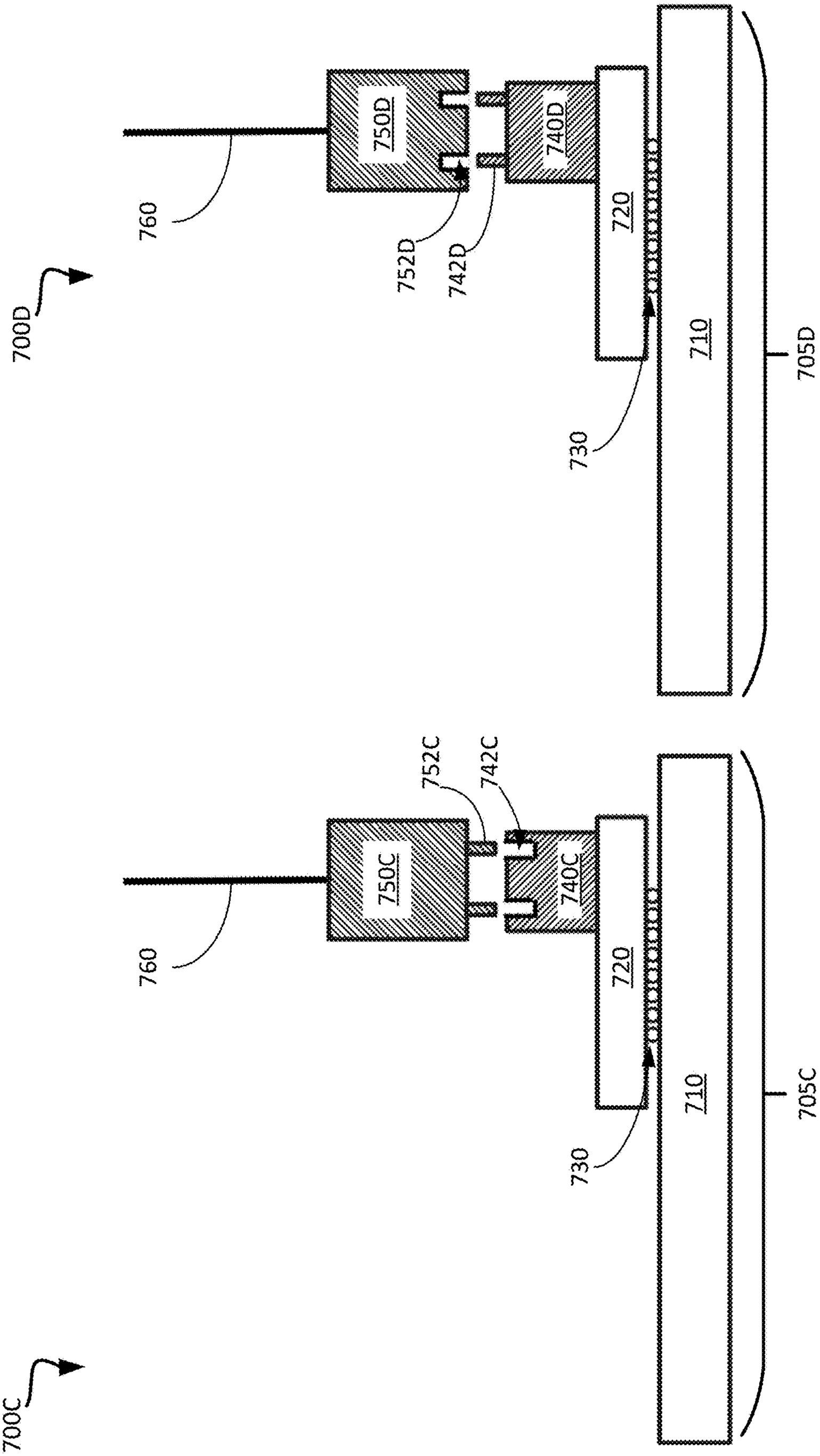

700D
760
750D
752D
742D
740D
720
710
730
705D

FIG. 7D

700C
760
750C
752C
742C
740C
720
710
730
705C

FIG. 7C

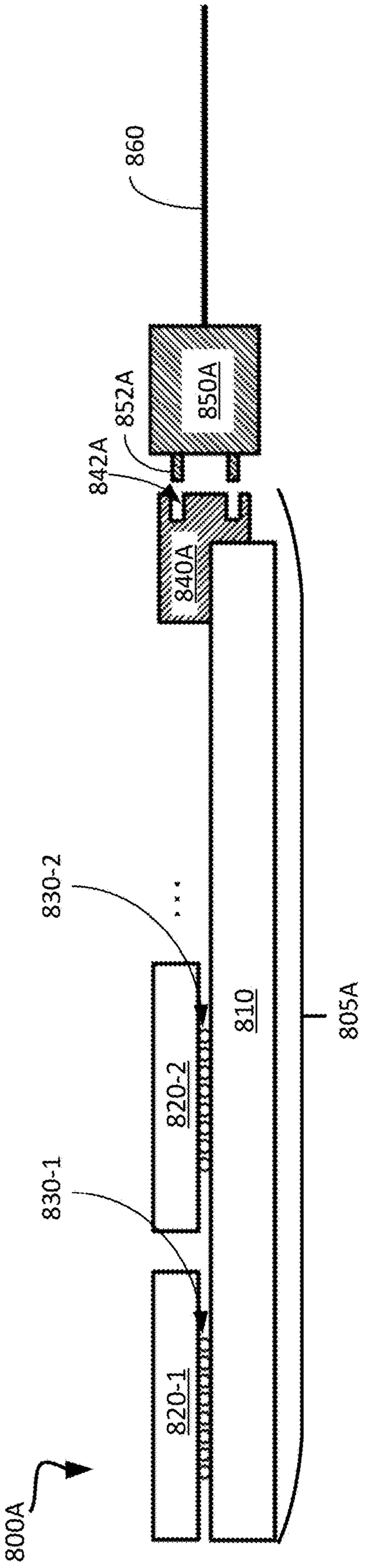

860
850A
852A
842A
840A
830-2
820-2
810
805A
830-1
820-1
800A

FIG. 8A

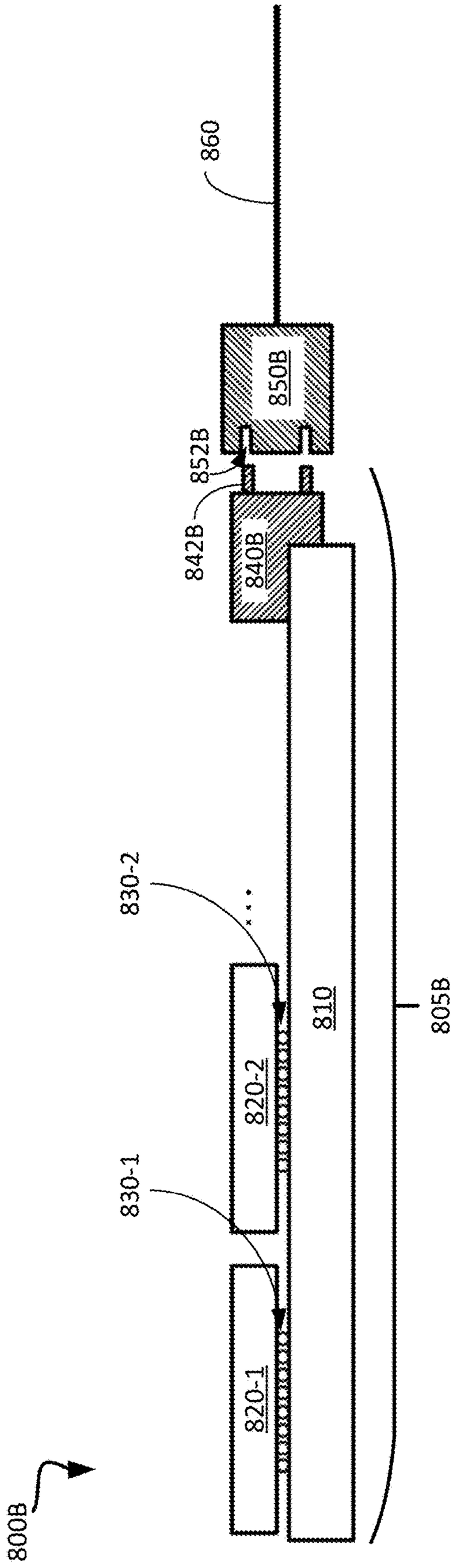

860
850B
852B
842B
840B
830-2
820-2
810
805B
830-1
820-1
800B

FIG. 8B

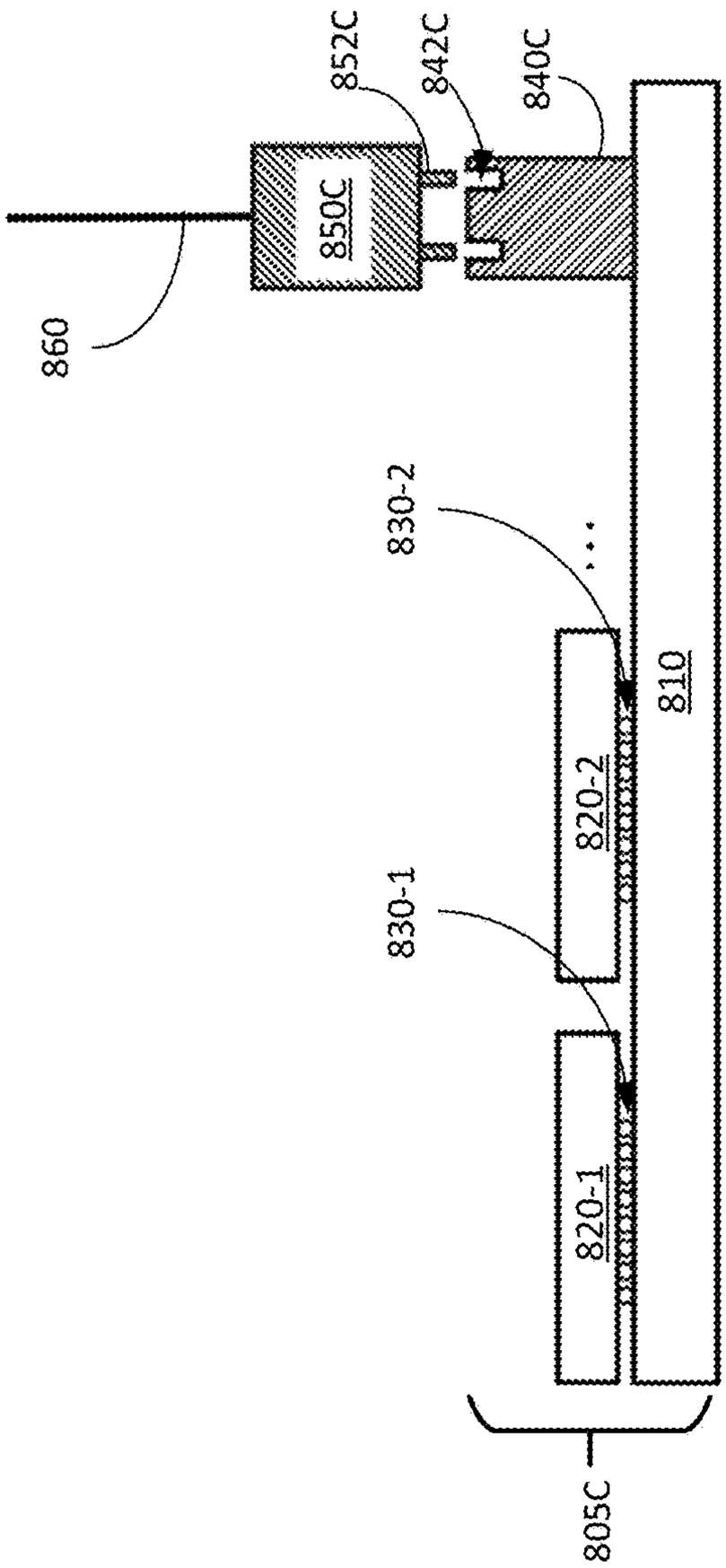

800C
805C
860
850C
852C
842C
840C
830-1
830-2
820-1
820-2
810

FIG. 8C

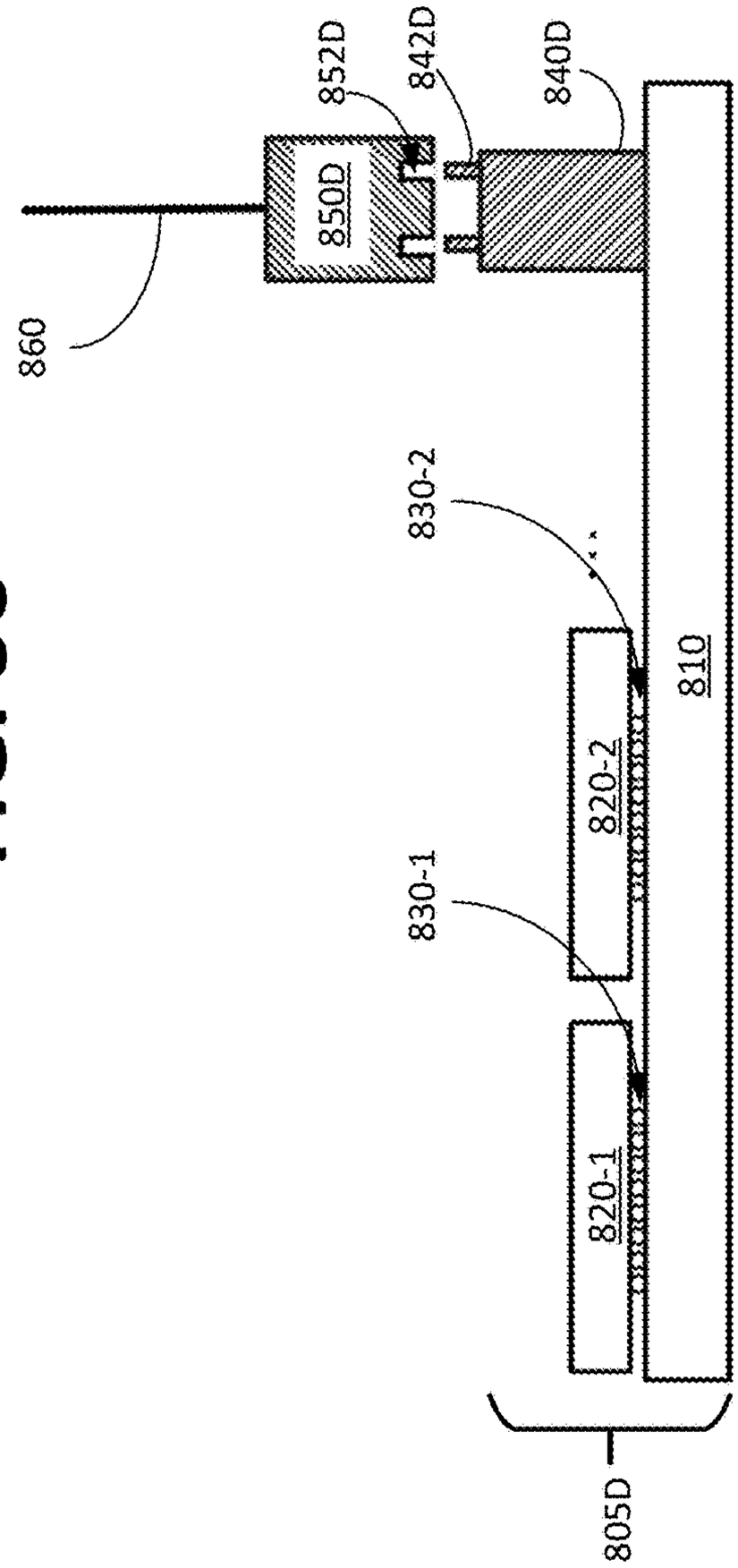

800D
805D
860
850D
852D
842D
840D
830-1
830-2
820-1
820-2
810

FIG. 8D

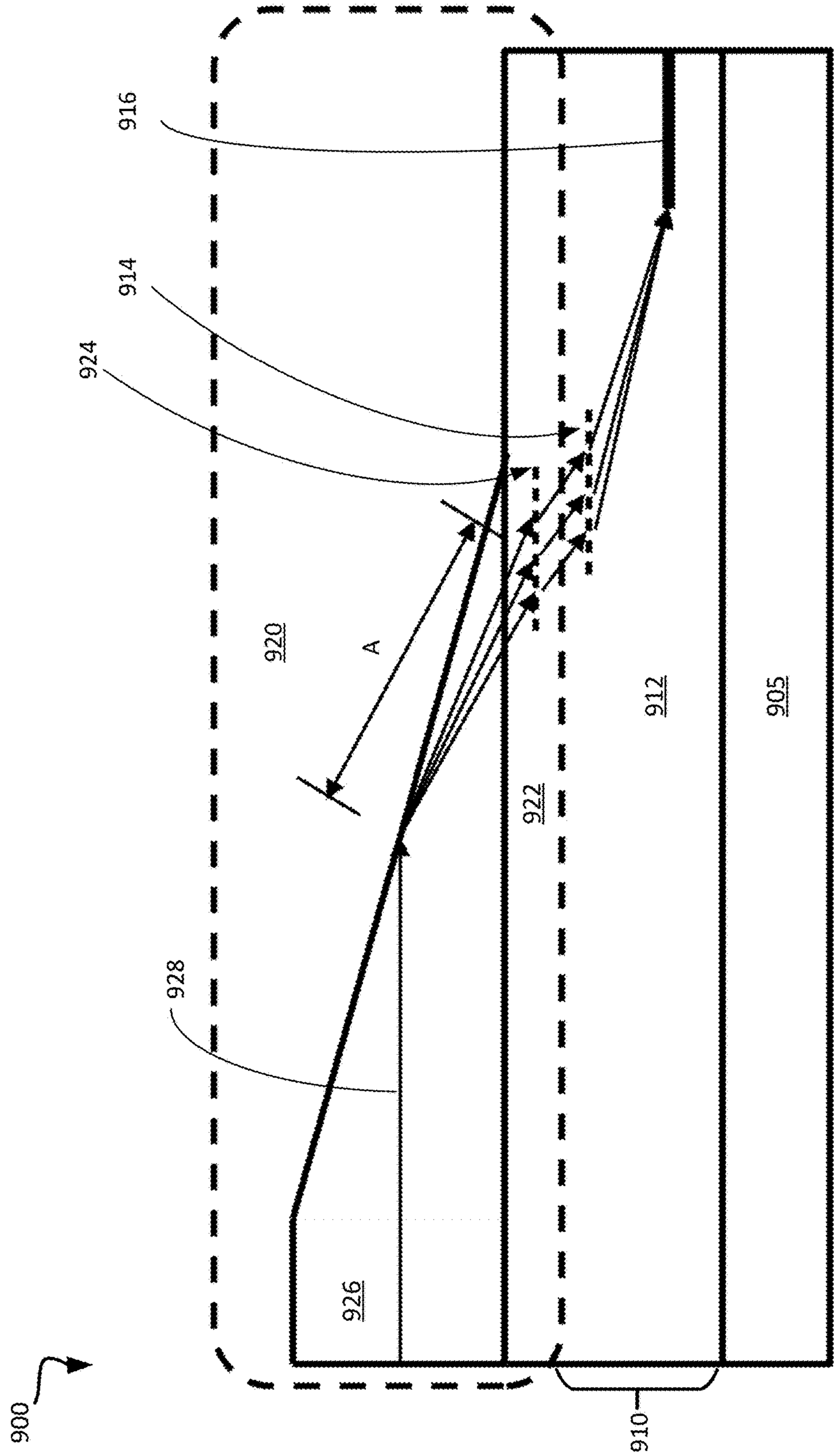


FIG. 9

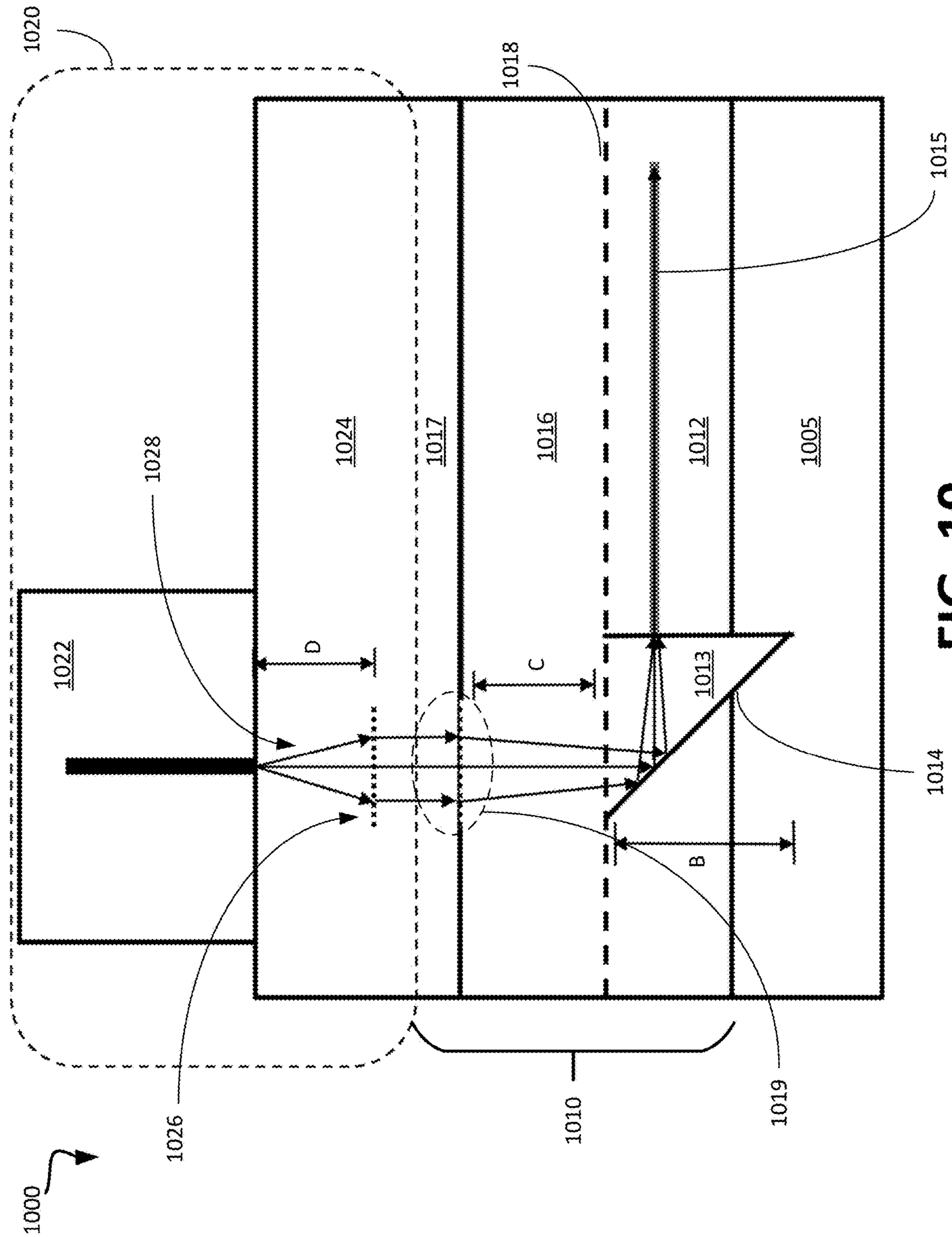

1020
1018
1015
1028
1024
1017
1016
1012
1005
1022
D
C
1013
1014
B
1026
1010
1019
1000

FIG. 10

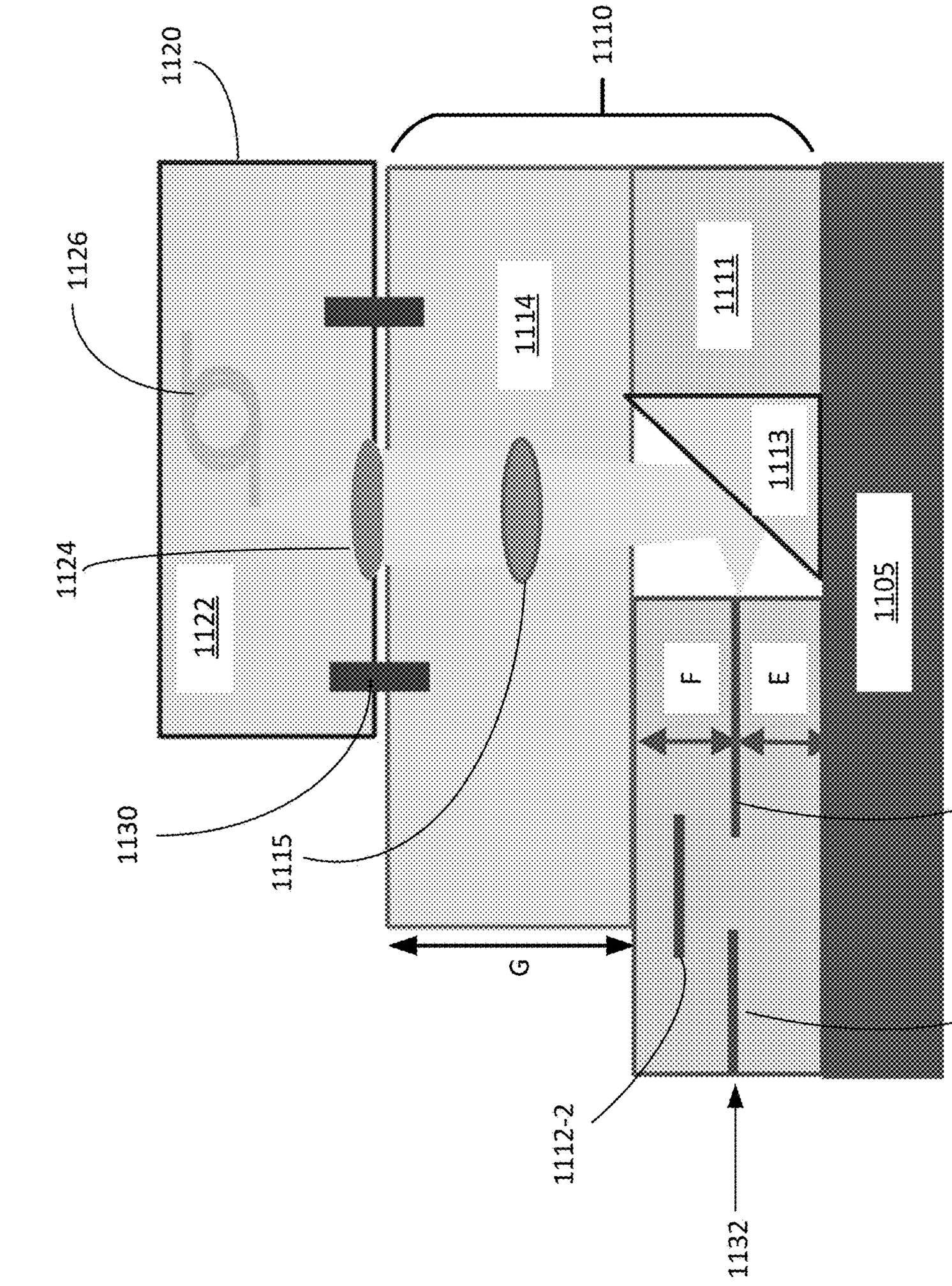

1100
1110
1120
1126
1124
1122
1130
1115
1114
1111
1113
1105
F
E
G
1112-3
1112-1
1112-2
1132

FIG. 11

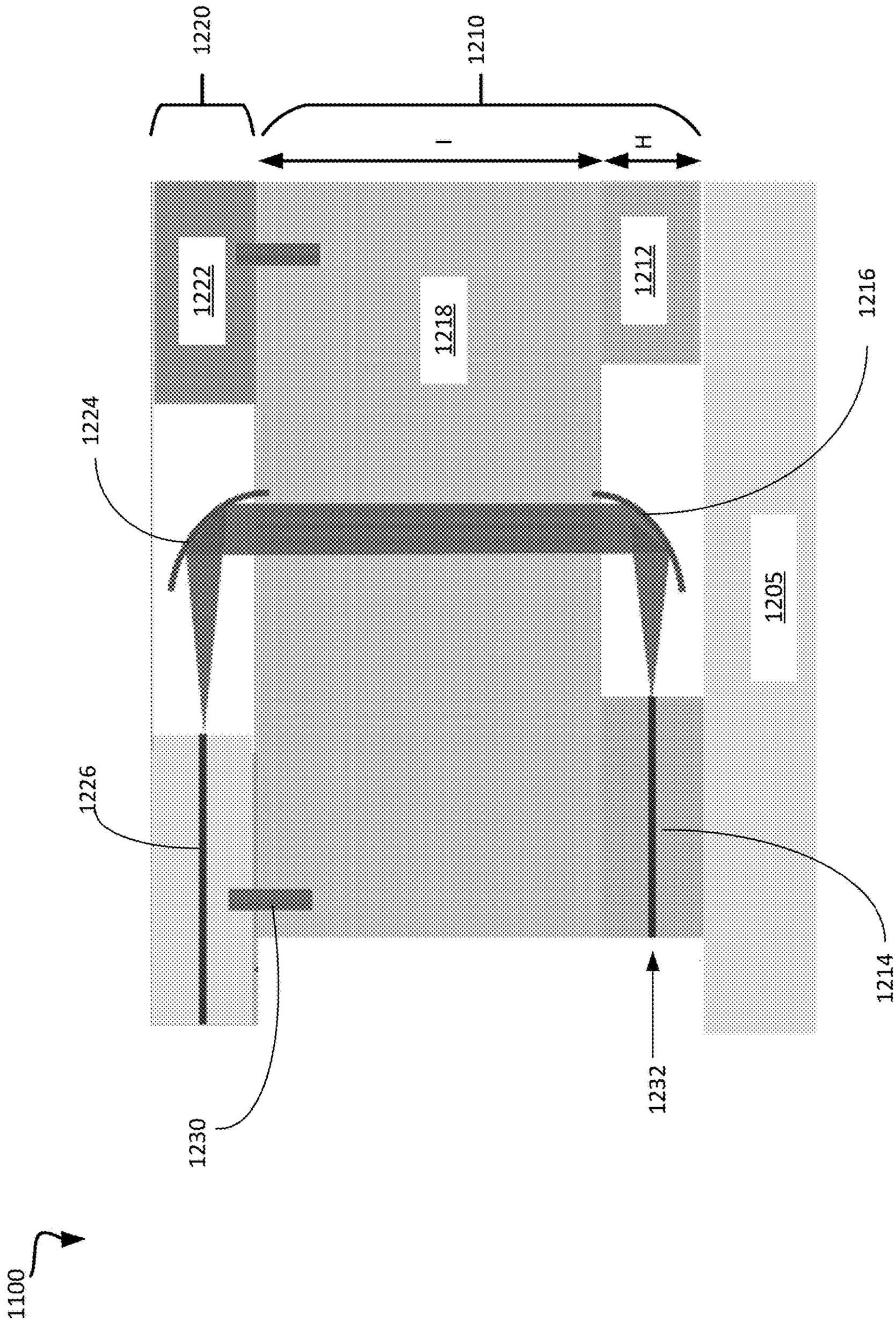

1220
1210
I
H
1222
1218
1212
1216
1224
1205
1226
1230
1232
1214
1100

FIG. 12

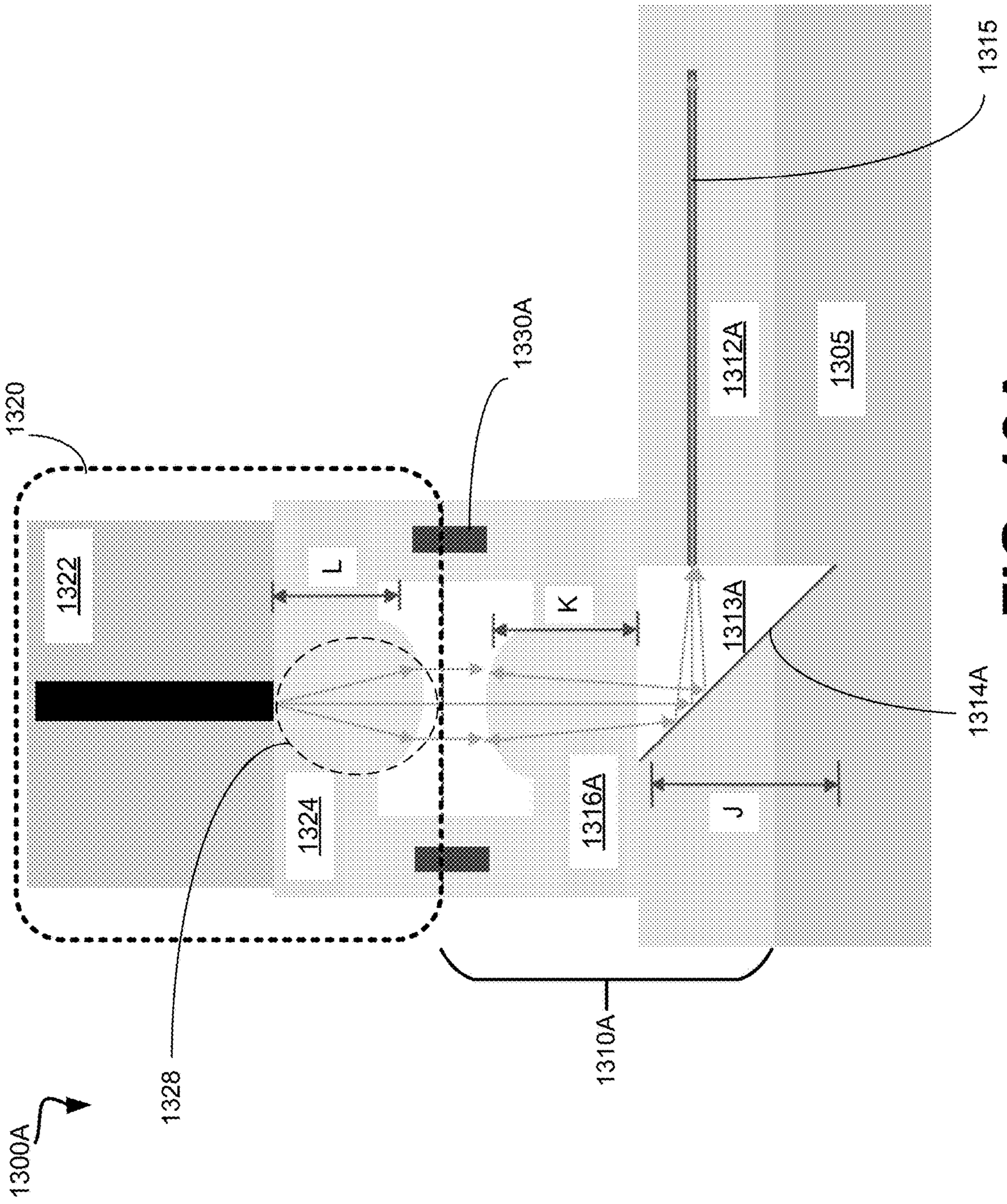

1315
1320
1330A
1322
L
K
1312A
1305
1313A
1324
1316A
1314A
J
1328
1310A
1300A

FIG. 13A

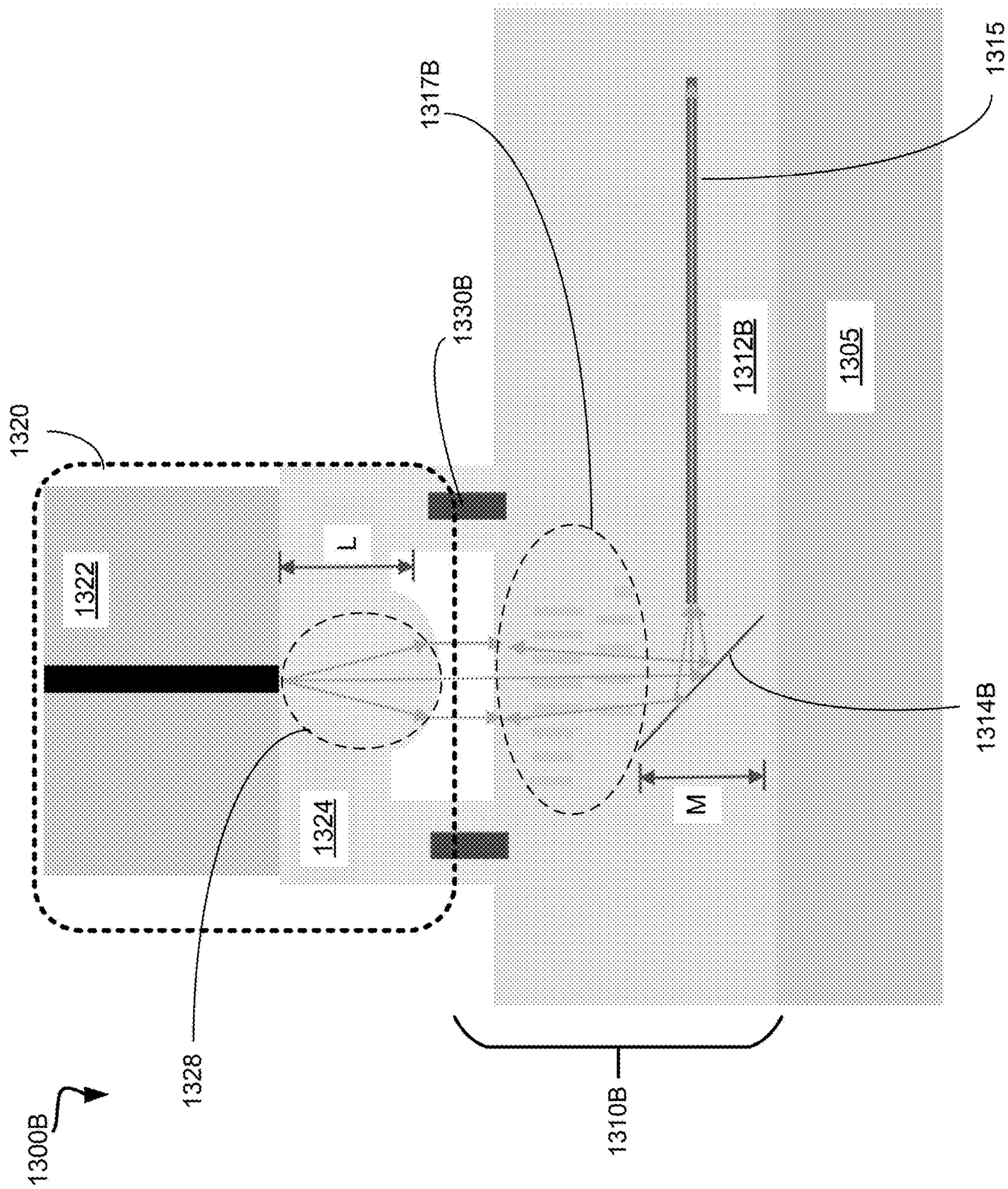

1315
1317B
1330B
1320
1322
L
1324
1328
1300B
1312B
1305
1314B
M
1310B

FIG. 13B

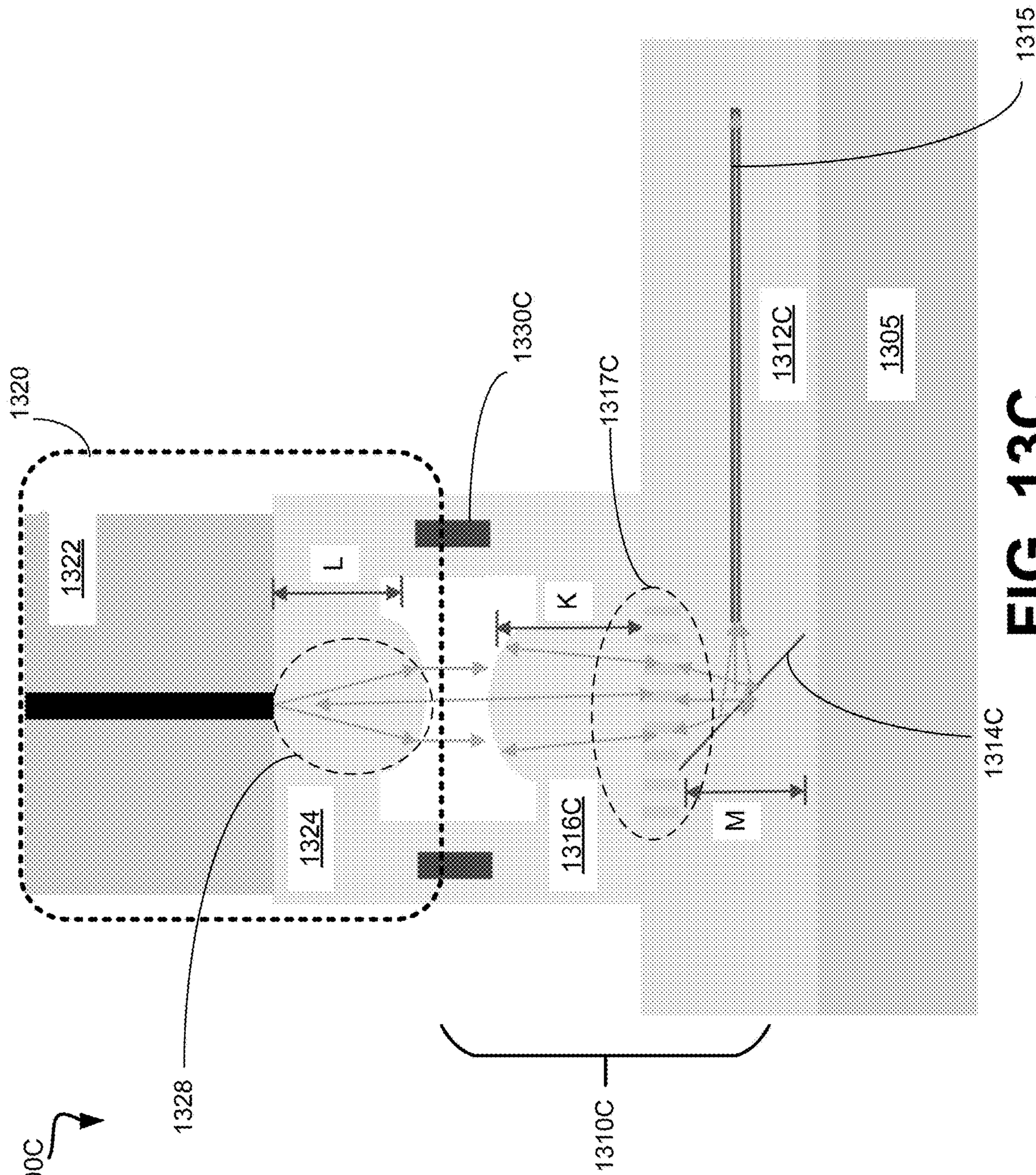

1315
1330C
1320
1317C
1322
1312C
1305
L
K
1324
1316C
M
1314C
1328
1300C
1310C

FIG. 13C

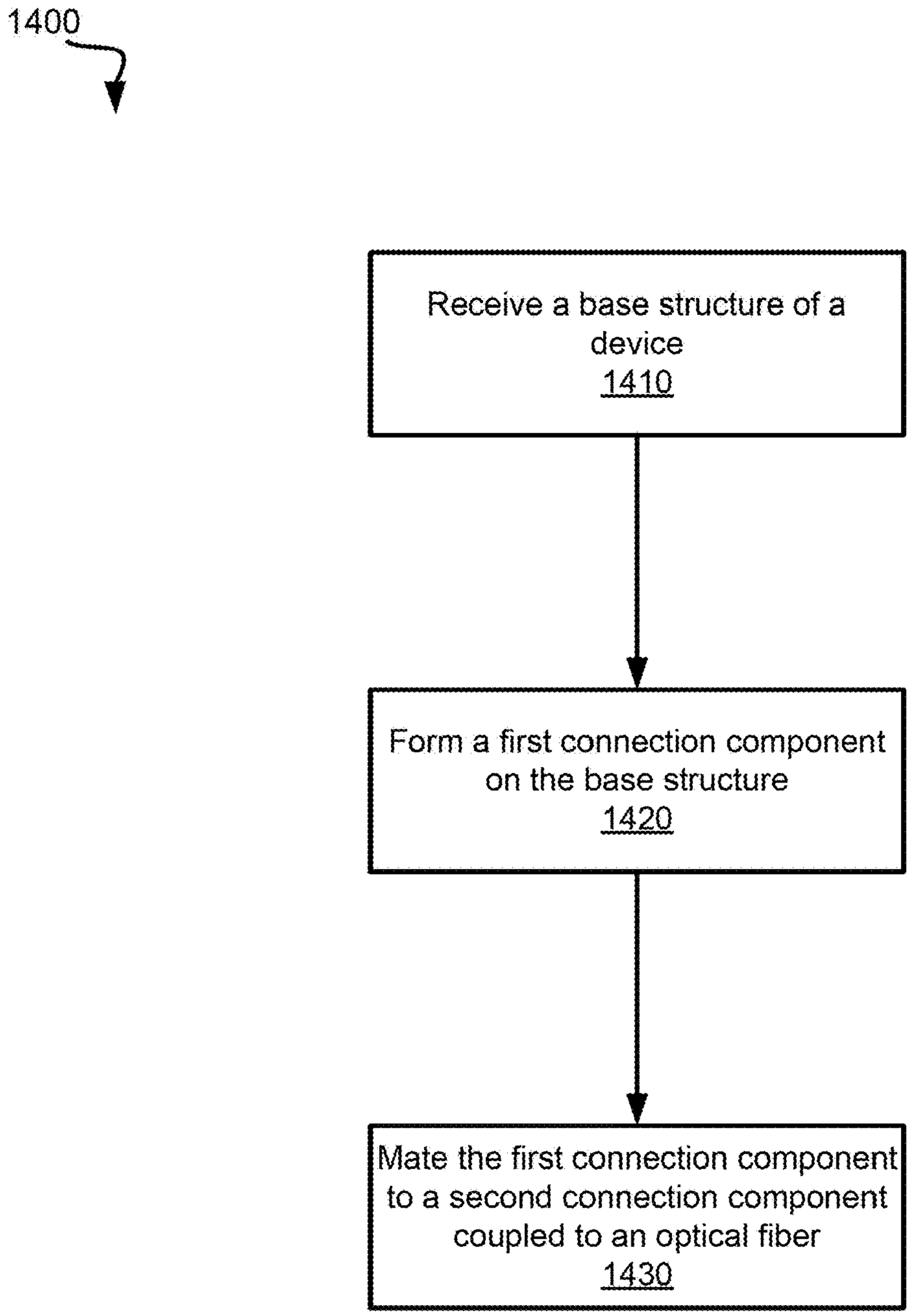

1400
Receive a base structure of a device
1410
Form a first connection component on the base structure
1420
Mate the first connection component to a second connection component coupled to an optical fiber
1430

FIG. 14

DETACHABLE OPTICAL FIBER-TO-WAVEGUIDE COUPLING

CROSS-REFERENCE TO RELATED APPLICATION(S)

[0001] The present application claims priority to U.S. Provisional Patent Application No. 63/550,754, filed on Feb. 7, 2024 and entitled "DETACHABLE OPTICAL FIBER-TO-WAVEGUIDE COUPLING", and U.S. Provisional Patent Application No. 63/704,096, filed on Oct. 7, 2024 and entitled "DETACHABLE OPTICAL FIBER-TO-WAVEGUIDE COUPLING", the entire contents of each of which are hereby incorporated by reference herein.

TECHNICAL FIELD

[0002] Embodiments of the present disclosure relate to optical systems, and more particularly to enabling detachable optical fiber-to-waveguide coupling.

BACKGROUND

[0003] In an optical system, an optical signal can travel through a waveguide (e.g., optical fiber) that is formed from an inner core made of a first material having a first index of refraction and an outer cladding made of a second material having a second index of refraction less than the first index of refraction. For example, the first material and the second material can each be formed from a different type of glass. Thus, when an optical signal traveling in a waveguide is incident on the boundary between the inner core and the outer cladding at an angle exceeding the critical angle, the optical signal can exhibit total internal reflection. At the boundary, an evanescent wave can be generated from the optical signal. Generally, an evanescent wave is an oscillating wave (e.g., electromagnetic wave or acoustic wave) generated at a boundary between two media and exists only within a very short distance from the boundary. Evanescent waves can exit the waveguide, and their amplitude can decay exponentially as a function of distance from the boundary. Thus, evanescent waves are generally observable in the near field of the optical signal in close proximity to the boundary.

[0004] Evanescent wave coupling generally refers to a (quantum) tunneling phenomenon in which an evanescent wave exiting a first medium excites a wave in an adjacent medium that is sufficiently close to the first medium. For example, in an optical communication system, evanescent wave coupling can occur when an evanescent wave generated within a waveguide excites an electromagnetic wave in an adjacent waveguide. Evanescent wave coupling can be accomplished when two waveguides are positioned close together such that the evanescent field generated by one of the waveguides reaches the other waveguide before any substantial decay of the evanescent wave is experienced.

SUMMARY

[0005] In some embodiments, a system includes a first connection component including a waveguide and a turning element formed on a base structure, the base structure including at least one photonic integrated circuit (PIC) formed on a substrate, and a detachable second connection component coupled to an optical fiber. The detachable second connection component is configured to mate with the first connection component to enable optical signal coupling between the optical fiber and the waveguide. The turning element is configured to at least one of: reflect a first optical signal received from the waveguide to the optical fiber, or reflect a second optical signal received from the optical fiber to the waveguide.

[0006] In some embodiments, a method includes receiving a base structure including at least one photonic integrated circuit (PIC) formed on a substrate, forming, on the base structure, a first connection component comprising a waveguide and a turning element, and mating the first connection component to a detachable second connection component coupled to an optical fiber to enable optical signal coupling between the optical fiber and the waveguide. The turning element is configured to at least one of: reflect a first optical signal received from the waveguide to the optical fiber, or reflect a second optical signal received from the optical fiber to the waveguide.

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] FIG. **1** is a diagram of a perspective view of at least a portion of a co-packaged substrate having one or more electrical and photonic devices formed thereon, in accordance some embodiments.

[0009] FIGS. **2**A-**2**B are diagrams of top views of photonic integrated interconnect units, according to some embodiments.

[0010] FIGS. **3**-**5** are diagrams of cross-sectional views of portions of a photonic integrated interconnect unit, according to some embodiments.

[0011] FIG. **6** is a diagram of a cross-sectional view of a portion of a pluggable connector, according to some embodiments.

[0012] FIGS. **7**A-**13**C are diagrams of views of example devices implementing detachable optical fiber-to-waveguide coupling, according to some embodiments.

[0013] FIG. **14** is a flowchart of an example method to fabricate a system to enable detachable optical fiber-to-waveguide coupling, according to some embodiments.

DETAILED DESCRIPTION

[0014] Embodiments of the present disclosure relate to enabling detachable optical fiber-to-waveguide coupling. 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 photonics integrated circuits 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.

[0015] A co-packaged device can include an interconnect device ("interconnect") formed 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 embodiments, 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.

[0016] Coupling of optical fibers to waveguides on a photonic integrated circuit (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 standard 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.

[0017] 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 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 multi-channel wavelength division multiplexing (WDM) optical system.

[0018] 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).

[0019] Typically, standard types of connectors in which an optical fiber is secured into a connection substrate do not support detachability of optical fibers from PICs. This limits the flexibility of optical fiber-to-waveguide coupling and makes it more difficult to repair a broken optical fiber secured within the connection substrate. Some non-standard (e.g., customized) connectors can be designed to enable detachability of the connectors from PICs. However, designing, fabricating and/or utilizing such non-standard connectors can, in comparison to standard connectors, add additional complexity and/or cost.

[0020] Some surface optical signal coupling solutions can use a grating coupler, formed in a cladding layer formed on a substrate, to direct an incoming optical signal into a waveguide formed by an inner core formed within the cladding layer. However, such coupling solutions can contribute to high loss (e.g., greater than or equal to about 2 decibels (dB)) and small 1-dB bandwidth in wavelength (e.g., less than or equal to about 30 nanometers (nm)). Alternatively, some surface coupling solutions can use a turning element, such as a mirror, formed in a cavity or trench formed within the cladding layer and the substrate, to direct an incoming optical signal into the waveguide formed by an inner core formed within the cladding layer. However, such coupling solutions may require turning element (e.g., mirror) alignment and bonding, which may not meet alignment tolerances for edge coupling (e.g., 1 dB alignment tolerance is typically less than or equal to about 2 micrometers (μm)).

[0021] Aspects and implementations described herein can address these and other drawbacks by enabling detachable optical fiber-to-waveguide coupling with standard optical fiber connector types. A co-packaged device described herein can include a substrate and at least one PIC formed on the substrate and in electrical communication with the substrate. For example, a ball grid array (e.g., array of solder balls) can be formed between the substrate and the PIC.

[0022] A connector system can include a first connection component integrated within the co-packaged device. In some embodiments, the first connection component is attached to the at least one PIC. In some embodiments, the first connection component is attached to the substrate.

[0023] The connector system can further include a second connection component coupled to an optical fiber. The first connection component and the second connection component can each be designed to have a geometry to enable the second connection component to be received by the first connection component.

[0024] In some embodiments, the first connection component is a female connection component having a set of openings, and the second connection component is a male connection component having a set of protrusions. In alternative embodiments, the first connection component is component is a male connection component having a set of protrusions, and the second connection component is a female connection component having a set of openings. Each opening is designed to receive a respective protrusion of the set of protrusions.

[0025] In some embodiments, the connector system enables optical fiber-to-waveguide coupling on a plane parallel to an upper surface of the substrate (e.g., horizontal coupling). For example, the first connection component can be attached to the PIC or the substrate in a manner enables the second connection component to be received along the plane parallel to the upper surface of the substrate.

[0026] In some embodiments, the connector system enables optical fiber-to-waveguide coupling on a plane perpendicular to (e.g., orthogonal to) the upper surface of the substrate (e.g., vertical coupling). For example, the first connection component can be attached to the PIC or the substrate in a manner enables the second connection component to be received along the plane perpendicular to the upper surface of the substrate.

[0027] Various types of connector systems enabling detachable optical fiber-to-waveguide coupling with detachable optical fiber connectors can be implemented in accordance with embodiments described herein.

[0028] In some embodiments, a connector system enabling detachable optical fiber-to-waveguide coupling with detachable optical fiber connectors is a cleaved optical fiber connector system. For example, the cleaved optical fiber connector system can be an angle-cleaved optical fiber connection system. In an angle-cleaved optical fiber connection system, the first connection component can include a cladding layer and the second connection component can include an angle-cleaved optical fiber. A first portion of a collimator assembly and a waveguide can be formed within the cladding layer, and the second connection component can include an angle-cleaved optical fiber and a second portion of the collimator assembly. A collimator assembly can include a set of lenses that can be used to collimate optical signals. In some embodiments, the collimator assembly is a meta-lens assembly. In some embodiments, the

collimator assembly is a microlens assembly. The angle-cleaved optical fiber is designed with a geometry and a cladding layer having a suitable index of refraction such that an optical signal can, upon incidence at a boundary between the angle-cleaved optical fiber and the atmosphere, be directed toward the collimator assembly via total internal reflection. The collimator assembly can be designed such that the optical signal is received by an end of the waveguide within the first connection component. Accordingly, an angle-cleaved optical fiber connector system can enable off-axis coupling. An example of an angle-cleaved optical fiber connector system will be described below with reference to FIG. **9**.

[0029] As another example, a cleaved optical fiber system can include a first connection component, and a second connection component including a cleaved optical fiber. The first connection component can include a first cladding layer formed on a first substrate and bonded to a second substrate, and a first portion of a second cladding layer formed on the second substrate. A turning element (e.g., mirror) and a waveguide can be formed within the first cladding layer. More specifically, a trench can be formed through at least the first cladding layer, and the turning element can be an angled mirror coated on a sidewall of the trench designed to reflect the optical signals toward the waveguide. A first portion of a collimator assembly can be formed about an interface between the second substrate and the first portion of the second cladding layer. The second connection component can further include a second portion of the second cladding layer formed underneath the cleaved optical fiber, and a second portion of the collimator assembly formed within the second portion of the second cladding layer. The collimator assembly can be designed such that optical signals are directed toward the turning element to enable the optical signals to be directed toward the waveguide. An example of this type of cleaved optical fiber connector system will be described below with reference to FIG. **10**.

[0030] In some embodiments, a connector system enabling detachable optical fiber-to-waveguide coupling with detachable optical fiber connectors is a refractive collimation optics connector system. For example, the first connection component can include a first layer and a second layer formed on the first layer. The first layer can be a cladding layer and a set of waveguides and a turning element (e.g., mirror) can be formed within the first layer. More specifically, the turning element can be formed within a cavity formed within the first layer. A first portion of a collimator assembly can be formed within the second layer, and the second connection component can include a second portion of the collimator assembly and an output optical fiber. In some embodiments, the collimator assembly is a meta-lens assembly. In some embodiments, the collimator assembly is a microlens assembly. An example of a connector system including a detachable optical fiber connector formed from a cleaved optical fiber, a collimator assembly, and an etched mirror to couple optical signals to a waveguide will be described below with reference to FIG. **11**.

[0031] In some embodiments, a connector system is a reflective collimation optics connector system. For example, the first connection component can include a cladding layer. A waveguide and a first portion of a collimator assembly can be formed within the cladding layer, and the second connection component can include a second portion of the collimator assembly and an output optical fiber. In some embodiments, the collimator assembly is a meta-lens assembly. In some embodiments, the collimator assembly is a microlens assembly. In some embodiments, the first connection component further includes a spacer layer formed on the cladding layer to provide additional separation between the first portion of the collimator assembly and the second portion of the collimator assembly. An example of a connector system including a detachable optical fiber connector formed from a cleaved optical fiber, a collimator assembly, and an etched mirror to couple optical signals to a waveguide will be described below with reference to FIG. **12**.

[0032] As another example, a cleaved optical fiber system can include a first connection component, and a second connection component attached to the first connection component. The first connection component can include a cladding layer formed on a substrate. A turning element (e.g., mirror) and a waveguide can be formed within the cladding layer. More specifically, a trench can be formed through at least the cladding layer, and the turning element can be an angled mirror coated on a sidewall of the trench designed to reflect the optical signals toward the waveguide. The second connection component can include a cleaved optical fiber. The first connection component includes a first portion of a collimator assembly formed on the cladding layer, and the second connection component includes a second portion of the collimator assembly formed underneath the cleaved optical fiber. The collimator assembly can be designed such that optical signals are directed toward the turning element to enable the optical signals to be directed toward the waveguide. In some embodiments, the first portion of the collimator assembly includes a first microlens, and the second portion of the collimator assembly includes a second microlens. An example of this type of cleaved optical fiber connector system will be described below with reference to FIG. **13**A. In some embodiments, the first portion of the collimator assembly includes a metalens array formed within the cladding layer, and the second portion of the collimator assembly includes a microlens. An example of this type of cleaved optical fiber connector system will be described below with reference to FIG. **13**B. In some embodiments, the first portion of the collimator assembly includes a first microlens, and a metalens array formed within the cladding layer, and the second portion of the collimator assembly includes a second microlens. An example of this type of cleaved optical fiber connector system will be described below with reference to FIG. **13**C.

[0033] A turning mirror described herein can reflect light up with accurate angle and position control, so that the collimator assembly (e.g., microlens and/or metalens array) can expand and collimate the light emitted from the waveguide into a large light beam (e.g., 30-150 um diameter). On the fiber connector side, the size of the light beam can be expanded from 10 um at the fiber core to 30-150 um after the microlens. Matching two large beam modes (30-150 um diameter) with low loss can become possible, as detachable mechanisms described herein can enable a 1 um-5 um alignment accuracy, which is tolerable for 30-150 um light beam sizes.

[0034] Embodiments described herein can provide for numerous other technical advantages. For example, embodiments described herein can enable detachable optical fiber-to-waveguide coupling with standard connector types, instead of non-standard connector types, which can reduce device complexity. As another example, embodiments

described herein can be used to enable detachable optical fiber-to-waveguide coupling with detachable optical fiber connectors formed from a cleaved optical fiber and meta-lens array, which can reduce device complexity (e.g., no grating coupler or drop-in mirror needed for coupling optical signals to a waveguide through a surface), reduce loss, increase bandwidth in wavelength and improve alignment accuracy.

[0035] FIG. **1** is a diagram of a perspective view of a system including a co-packaged device **100**, in accordance some embodiments. The co-packaged device **100** can include an electrical or opto-electrical chip ("chip") **102** connected by a waveguides or electrical trace interconnect **104** to a photonic integrated interconnect unit **103** where all are formed on or formed on a package substrate **101**. In some embodiments, the chip **102** includes any high-density chip having a high input/output (I/O) pin count. In one example, the high-density chip has between **100** and **2000** I/O pins or up to and greater than **2000** I/O pin counts. For example, the chip **102** can be a data center SWITCH chips, an artificial intelligence (AI) chip, etc.

[0036] The photonic integrated interconnect unit **103** includes a fiber connector region configured to be coupled to a fiber connector **112** for removably connecting a fiber cable **120** to the photonic integrated interconnect unit **103**. In some embodiments, the fiber cable **120** is plugged into the fiber connector **112** to operably connect the fiber cable **120** to the co-packaged device **100**. In an embodiment, the photonic integrated interconnect unit **103** is configured for connecting fiber cables **120** including, but not limited to, single-mode fiber optic cables having 9 um fiber core diameters. The fiber connector **112** may further include optical fibers **112**A (FIG. **4**) to operably connect fiber cables **120** having between 1 to 74 fiber cores, 74 to 148 fiber cores, and up to and greater than 148 fiber cores to the photonic integrated interconnect unit **103**.

[0037] In some embodiments, the photonic integrated interconnect unit **103** is configured to transmit signals between the chip **102** and the fiber cable **120** connected to the photonic integrated interconnect unit **103**. The photonic integrated interconnect unit **103** includes a photonic glass layer (PGL) substrate **106**, optical structures $\mathbf{110}_1$-$\mathbf{110}_N$ formed integral with or on the PGL substrate **106**, an optical transceiver integrated circuit (chip) **108** mounted on the PGL substrate **106** and coupled to the optical structures $\mathbf{110}_1$-$\mathbf{110}_N$ at a first interface **107**, and the fiber connector **112** connected to both the PGL substrate **106** and the optical structures $\mathbf{110}_1$-$\mathbf{110}_N$ at a second interface **109**.

[0038] The chip **108** operates to convert electrical signals to optical signals, and vice versa. In some embodiments, the chip **108** is a silicon photonic (SiPho) chip. The optical structures $\mathbf{110}_1$-$\mathbf{110}_N$ operate to transmit optical signals between the chip **108** and the fiber connector **112**, and the optical waveguide or electrical trace interconnect **104** operate to transmit electrical or optical signals between the photonic integrated interconnect unit **103** (e.g., the chip **108**) and the chip **102**. The optical waveguide or electrical trace interconnect **104** can include metal traces that are formed within the package substrate **101**, which in some embodiments can include metal traces formed in a printed circuit board (PCB) substrate or metal traces formed within multiple redistribution layers (e.g., dielectric containing layers) formed over a solid core substrate (e.g., silicon or glass core substrate).

[0039] A photonic engine **105** may optionally further include one or more electronic phy chips **111** that are coupled to the chip **108**. The electronic phy chip **111** is generally used to assist with operations performed by an optical chip. In some embodiments, the electronic phy chip **111** is operably connected to the chip **108** to assist the chip **108** with various electrical functions. As shown, the electronic phy chips **111** may be mounted on top of the chip **108** and thereby directly connected to the chip **108**. Alternatively, the electronic phy chip **111** may be embedded in the PGL substrate **106** and connected to the chip **108** through the PGL substrate **106**, which is often simply referred to herein as a substrate **106**. Further, the electronic phy chip **111** can be mounted on or embedded in the package substrate **101** and connected to the chip **108** through electrical interconnect **104**.

[0040] FIGS. **2**A-**2**B are diagrams of top views of the photonic engine **105**, according to some embodiments. As shown in FIG. **2**A, the photonic engine **103** includes the chip **108** mounted near one end of the PGL substrate **106**, the fiber connector **112** connected at an opposite end of the PGL substrate **106** from the chip **108**, and the optical structures $\mathbf{110}_1$-$\mathbf{110}_N$ extending between the chip **108** and the fiber connector **112**. In some embodiments, each of the optical structures $\mathbf{110}_1$-$\mathbf{110}_N$ include a light transmitting region for transmitting light in either direction between the first interface **107** and the second interface **109**. The light being transmitted through the optical structures can be either received from one or more waveguides **108**A (FIG. **2**B) of the chip **108** or received from one or more optical fibers within the fiber connector **112** that a light signal source is in communication with during use. The chip **108** is typically configured to receive light (e.g., detect) transmitted through the optical structures $\mathbf{110}_1$-$\mathbf{110}_N$ and also emit light (e.g., transmit) into the optical structures $\mathbf{110}_1$-$\mathbf{110}_N$ in an effort to communicate with external devices connected through the fiber connector **112**. The chip **108** can be configured to transmit light into the optical structures $\mathbf{110}_1$-$\mathbf{110}_N$ by at least the use of light emitters integrated into chip **108**, or by use of light emitters that are external to PGL substrate **106**. In the case where the light emitters are external to PGL substrate **106** the light is delivered to chip **108** via the optical structures $\mathbf{110}_1$-$\mathbf{110}_N$ and then modulated by the chip **108** to create a transmit signal that is provided to the optical structures $\mathbf{110}_1$-$\mathbf{110}_N$. In some embodiments, which can be combined with other embodiments described herein, the optical structures $\mathbf{110}_1$-$\mathbf{110}_N$ are formed on (e.g. directly or indirectly) or are integral with the PGL substrate **106**.

[0041] In some embodiments, which can be combined with other embodiments described herein, the light transmitting region within each of the optical structures $\mathbf{110}_1$-$\mathbf{110}_N$ may have the same cross-sectional dimensions, such as height and width. In another embodiment, which can be combined with other embodiments described herein, the light transmitting region within at least one of the optical structures $\mathbf{110}_1$-$\mathbf{110}_N$ may have at least one different cross-sectional dimensions, such as one of height and width, from the dimensions of the other optical structures **110** within the PGL substrate **106**. In one embodiment, which can be combined with other embodiments described herein, the light transmitting region within each of the optical structures $\mathbf{110}_1$-$\mathbf{110}_N$ may have the same refractive index. In another embodiment, which can be combined with other embodiments described herein, the light transmitting region within

at least one of the optical structures **110**$_1$-**110**$_N$ may have a different refractive index or multiple different refractive indexes or a gradual gradation of refractive indexes or other index varying structures when compared with the rest of the optical structures **110**$_1$-**110**$_N$ within the PGL substrate **106**.

[0042] In some embodiments, the number of optical structures **110**$_1$-**110**$_N$ formed in the PGL substrate **106** is dependent on the number of waveguides **108**A in the chip **108** needing to be connected, which may also correspond with the number of fiber connections to be connected to the chip **102**. In some embodiments, the chip **102** may comprise seventy-two (72) fiber connections such that seventy-two (72) corresponding interconnects **104** extend from the chip **102** and connect to seventy-two (72) corresponding fibers and waveguides **108**A in the chip **108** of the photonic engine **105**. To appropriately connect the chip **108** to the fiber connector **112** via the optical structures **110**$_1$-**110**$_N$ in the photonic glass layer substrate **106**, seventy-two (72) corresponding optical structures **110** are formed on or integral with the PGL substrate **106**. In this example, as shown in FIGS. **2**A-**2**B, N equals 72, and thus the optical structures **110** are spaced apart in the X-Y plane from one edge of the PGL substrate **106** to the other edge of the PGL substrate **106**. In this example, optical structure **110**$_1$ is positioned near the top-most edge and optical structure **110**$_{72}$ would be positioned closest to the bottom most edge of FIG. **2**A. As discussed further below, the optical structures **110**$_1$-**110**$_N$ are spaced apart and separated by a material that has different optical properties, such as index of refraction (n), than the light transmitting portions of the optical structures **110**$_1$-**110**$_N$.

[0043] The optical structures **110**$_1$-**110**$_N$ are generally sized and configured to appropriately connect to the waveguides **108**A within the chip **108**. In an embodiment, the waveguides **108**A (FIG. **2**B) at the output of the chip **108**, or portion that is to communicate with the optical structures, have a core with a height dimension that is about 1 um in cross-sectional size. In one configuration, the output of the chip **108** has a square or rectangular shaped cross-section that has at least one dimension that is equal to about 1 μm in length. For example, a square cross-section of a waveguide **108**A may have a core that is 1 μm height and width. Light transmitted to and from the chip **108** would thus be transferred through the 1 μm waveguides **108**A.

[0044] In contrast, light transmitted to and from the fiber cable **120** through the fiber connector **112** can have a different form factor, such as having a core cross sectional dimension of about 9 μm in size. For example, the fiber connector **112** may have a square, rectangular or circular cross-section with a core having a height dimension that is about 9 μm in size. As such, in some embodiments, each of the optical structures **110**$_1$-**110**$_N$ is formed such that light propagating through the optical structures **110**$_1$-**110**$_N$ between the chip **108** and the fiber cable **120** is expanded or compressed accordingly depending on the direction of propagation of the optical signal. In one example, the optical structures **110**$_1$-**110**$_N$ extending from the second interface **109** adjacent to the 9 μm fibers in the fiber connector **112** have transmission regions with cross-sectional areas that vary at different portions of the respective structures to facilitate coupling to the 1 μm waveguides **108**A in the chip **108**. In one embodiment, the optical structures **110**$_1$-**110**$_N$ are tapered along at least a portion of their length from a 9 μm dimensional core size until they are near 1 μm dimensional core size near the first interface **107**, where it is assumed that the varying dimensional core size relates to a dimension of a side of a square or rectangular cross-sectional shaped optical structure **110**. In some embodiments, the tapered optical structures **110** have a cross-sectional area ratio, which if measured at one end versus measured at the opposing end of the optical structure **110** is greater that 1:1 and less than about 1:100, or less than 1:81. In some embodiments, the optical structures **110**$_1$-**110**$_N$ extending from the second interface **109** adjacent to the fiber connector **112** have a varying refractive index along at least a portion of their length from the second interface **109** to the first interface **107** to facilitate coupling between the optical elements within the chip **108** and the fiber connector **112** that have different cross-sectional dimensions.

[0045] In another aspect, the photonic engine **105** is configured such that the transmission loss of the optical signal between the first interface **107** and the second interface **109** is approximately or less than 3 dB, inclusive of loss due to the transmission of the optical signal through the optical structures **110**$_1$-**110**$_N$ themselves. In some embodiments, the transmission loss may largely be dependent on the coupling at the first interface **107** between the chip **108** and the optical structures **110**$_1$-**110**$_N$. As shown in FIG. **2**B, in an embodiment, the chip **108** is to be mounted on a coupling surface **208** at a chip mounting region **204** of the PGL substrate **106**. When mounted on chip mounting region **204**, the waveguides **108**A formed on the side surface **108**B of the chip **108** are aligned with the optical structures **110**$_1$-**110**$_N$ found at the first interface **107**.

[0046] In some embodiments, the PGL substrate **106** further includes one or more fiducial marks **206** to assist in the alignment and mounting of the chip **108** on the chip mounting region **204**. The one or more fiducial marks **206** operate to guide and help align the position of the chip **108** along the X-Y plane of the PGL substrate **106** to ensure mounting of the chip **108** occurs with proper alignment to one or more electrical contacts (e.g., vias **1006**) and optical structure portions of the PGL substrate **106**. As such, in an embodiment, the tolerance for error in the coupling or hybrid bonding the chip **108** and the optical structures **110**$_1$-**110**$_N$ together at the first interface **107**, which will be discussed further below, may be in a range from 0.1 to 2 μm to ensure the connections are optimized for the lowest signal loss. In one embodiment, the misalignment of the centers of the waveguides **108**A and the optical structures **110**$_1$-**110**$_N$ is maintained such that the lateral misalignment in the Y-direction (i.e., top to bottom direction in FIG. **2**B) is less than 1 to 2 μm. In some embodiments, the misalignment of the centers of the waveguides **108**A and the optical structures **110**$_1$-**110**$_N$ is also maintained such that the vertical misalignment in the Z-direction (FIGS. **4**-**5**) is less than 1 to 2 μm. In one embodiment, the variability in the vertical misalignment can be dependent on the variability of the compression of solder balls **1011** or other electrical contact that is used to electrically couple the chip **108** to vias **1006** (shown in FIGS. **4**-**5**) formed in a portion of the PGL substrate **106**.

[0047] FIG. **3** is a diagram of a schematic, cross-sectional end view of a portion of the photonic engine **105** mounted on the package substrate **101** formed by use of the sectioning line C-C in FIG. **4**., according to some embodiments. As shown in FIG. **3**, the photonic engine **105** includes a bottom surface **106**A of the photonic glass layer substrate **106** formed on a top surface **101**A of the package substrate **101**,

with the optical structures $\mathbf{110}_1$-$\mathbf{110}_N$ extending through the PGL substrate **106**. As shown, the optical structures $\mathbf{110}_1$-$\mathbf{110}_N$ extending through the PGL substrate **106** are each aligned in the X-Z plane of the PGL substrate **106**. While FIG. **3** shows the optical structures $\mathbf{110}_1$-$\mathbf{110}_N$ formed in a single row in plane across the PGL substrate **106**, other arrangements of the optical structures $\mathbf{110}_1$-$\mathbf{110}_N$ may be formed in the PGL substrate **106**. For example, more than a single row of optical structures may be formed and stacked vertically. The arrangements of the optical structures $\mathbf{110}_1$-$\mathbf{110}_N$ is not intended to limit the scope of the disclosure provided herein.

[0048] FIG. **4** is a schematic, transverse cross-sectional lateral view of a portion of the photonic engine **105** mounted on the package substrate **101** that is formed by use of the sectioning line B-B in FIG. **2**A, according to some embodiments. As shown in FIG. **4**, the package substrate **101** includes circuit traces **1002** extending from interconnect pads **1004** formed integral in the top surface **101**A of package substrate **101**. In some embodiments, the circuit traces **1002** form the interconnects **104** that electrically connect the photonic engine **105** in contact with the interconnect pads **1004** to the chip **102**. Alternatively, the circuit traces **1002** may electrically connect the photonic engine **105** in contact with the interconnect pads **1004** to other integrated circuits formed on the package substrate **101**.

[0049] In some embodiments, the vias **1006** extend through a portion of the PGL substrate **106** between the coupling surface **208** and the bottom surface **106**A of the PGL substrate **106**. When the photonic engine **105** is mounted to the package substrate **101**, the vias **1006** can be aligned with and placed in electrical contact with the corresponding interconnect pads **1004** that are exposed on the top surface **101**A of package substrate **101** and are in electrical connection with the photonic integrated interconnect unit **103** through the circuit traces **1002** formed in the package substrate **101**. In some embodiments, the vias **1006** alternatively connect the photonic engine **105** to one or more other integrated circuits (chips) embedded in the package substrate **101** or on the package substrate **101**.

[0050] As shown in FIG. **4**, the chip **108** can be actively or passively mounted on the coupling surface **208** of the PGL substrate **106** with the side surface **108**B of the chip **108** are "butt-coupled" to an end surface **106**B of the PGL substrate **106** at the first interface **107**. When the chip **108** is butt-coupled to the end surface **106**B of the PGL substrate **106**, the end of the waveguide **108**A in the chip **108** is also butt-coupled to a corresponding end of the optical structure **110**, such as optical structure **1103**, formed in the PGL substrate **106** at a fourth coupling interface **1008**. The coupling of the waveguides **108**A to the optical structures **110** at the fourth interface **1008** can impact the loss of optical signals between the chip **108** and the PGL substrate **106**. As such, to minimize coupling loss, the aforementioned one or more fiducial marks **206** (FIG. **2**B) are used during mounting of the chip **108** to assist in alignment and the precise placement of the chip **108** to optimize the butt-coupling of the waveguides **108**A and the optical structures $\mathbf{110}_1$-$\mathbf{110}_N$ at the fourth interface **1008** and minimize coupling loss.

[0051] To connect the chip **108** to the PGL substrate **106**, chip **108** further includes solder connects **1012** that are in contact with the solder balls **1011**, wherein the solder balls **1011** are positioned between the solder connects **1012** and an end of each of the vias **1006** on the coupling surface **208**. The solder balls **1011** electrically connect the chip **108** to the vias **1006** formed in the photonic glass layer substrate **106**. In some embodiments, the solder balls or other interconnect bumps, pillars or interconnect materials, including planar hybrid bonding techniques, **1010** are used to connect the solder connects **1012** to the vias **1006** extending through the PGL substrate **106** to the package substrate **101**. In the embodiment shown, the solder balls **1011** and the vias **1006** connect the solder connects **1012** to the plurality of interconnect pads **1004** in the package substrate **101**, thereby electrically connecting the chip **108** to the circuit traces **1002** in the package substrate **101** connected to the plurality of interconnect pads **1004**.

[0052] In some embodiments, the coupling surface **208** of the PGL substrate **106** further includes a plurality of recesses (not shown) for cradling each of the solder balls **1011** used to connect the solder connects **1012** in the chip **108** and the vias **1006** in the PGL substrate **106**. The recesses may be formed to allow for expansion of the solder balls **1011** when flattened such that the contacting surface of the solder balls **1011** may be substantially flush with the coupling surface **208**. The flattening of the solder balls **1011** on the coupling surface **208** when contacting the solder connects **1012** in the chip **108** helps ensure uniformity in the mounting of the chip **108** on the PGL substrate **106** as well as increases contact reliability of the solder balls **1011**.

[0053] FIG. **4** also includes a cross-sectional view of a portion of the fiber connector **112** that is coupled to a portion of the PGL substrate **106** at the interface **109**, according to some embodiments. The fiber connector **112** can be removably connected to a portion of the photonic engine **105** to allow the transmission to and receipt of optical signals from the optical structures **110** by use of a "butt-coupled" connection configuration.

[0054] FIG. **5** is a schematic, cross-sectional lateral view of a portion of the photonic engine **105** mounted on the package substrate **101**, according to some embodiments. As shown, the chip **108** may be passively mounted on the photonic glass layer substrate **106** in a second chip mounting region **1106** of the photonic glass layer substrate **106**. The second chip mounting region **1106** of the PGL substrate **106** further includes a coupling portion **1102** of each of the optical structures $\mathbf{110}_1$-$\mathbf{110}_N$ extending along a coupling surface **1104** of the PGL substrate **106**. When the chip **108** is mounted on the second chip mounting region **1106**, a portion of the waveguides **108**A in the chip **108** are evanescently coupled with a surface of the corresponding coupling portions **1102** of each of the optical structures $\mathbf{110}_1$-$\mathbf{110}_N$ in the PGL substrate **106**. The evanescent wave coupling of the waveguides **108**A to the optical structures **110** allow for optical signals to be transferred between the coupled waveguides.

[0055] In some embodiments, the evanescently coupling of the waveguides may be formed as a directional coupler wherein the evanescent modes of one waveguide overlap with the modes of a second waveguide. When the evanescent modes of the waveguides overlap, evanescent fields generated by the respective waveguides also overlap such that the evanescent field generated by one waveguide may excite a wave in the other waveguide. As such, in one aspect, the coupling strength between the waveguides **108**A and the optical structures **110** may therefore be sensitive to the distance between the waveguides **108**A and optical structures **110**, and/or the length of the coupling portion **1102**.

The coupling portion **1102** and respective contacting portion of the waveguides **108**A may therefore be sized and formed to optimize the coupling and minimize coupling loss.

[0056] The mounting of the chip **108** on the substrate **106** in the chip mounting region **1106** of the substrate **106** further includes connecting the solder connects **1012** in the chip **108** to the vias **1006** in the PGL substrate **106** using the solder balls **1011**. The solder balls **1011** may be positioned on the coupling surface **208** adjacent to the coupling portions **1102** of the optical structures $\mathbf{110}_1$-$\mathbf{110}_N$ and aligned between each respective solder connects **1012** and via **1006**. The solder balls **1011** may be sized such that when the solder balls **1011** is flattened due to the contact of the chip **108** being mounted on the PGL substrate **106**, the solder balls **1011** is flattened to a height substantially the same as the height of the coupling portions **1102** of the optical structures $\mathbf{110}_1$-$\mathbf{110}_N$. In the embodiment shown, the solder balls **1011** in contact with the vias **1006** and the interconnect pads **1004** electrically connect the chip **108** to the circuit traces **1002** in the package substrate **101**. Further, one or more stand-off structures **1015** can be used to position, support and/or help align the chip **108** within the chip mounting region **204**. In one example, the stand-off structures **1015** (FIG. **4**) are formed to help set the vertical alignment of the waveguides **108**A with the optical structures **110**. In some embodiments, the PGL substrate **106** includes one or more stand-off structures **1015** that are configured to support the chip **108** in a direction (e.g., Z-direction) that is substantially perpendicular to a plane that is parallel to the plane in which the optical structures $\mathbf{110}_1$-$\mathbf{110}_N$ extend (e.g., X-Y-plane).

[0057] FIG. **6** is a schematic, cross-sectional lateral view of the fiber connector **112** portion of the photonic engine **105**, according to some embodiments. In general, the fiber connector **112** is used to removably connect the external fiber cable **120** to the photonic engine **105**. The optical fibers **112**A of the fiber connector **112** transmit light signals to and from the fiber cable **120** plugged into the fiber connector **112**. The fiber connector **112** is configured to allow for the attachment of external fiber cable **120** to the optical input/output of the photonic engine **105** without requiring active alignment of the fiber cable **120** to the photonic engine **105** on a per fiber core basis. As such, the fiber connector **120** may be formed and configured to be interoperable with a variety of different fiber cable **120** assemblies and standards. Light transmitted along the fibers **112**A is directed to the optical structures $\mathbf{110}_1$-$\mathbf{110}_N$ on the PGL substrate **106** by a lens assembly for subsequent transmittance to and through the photonic engine **105**. The lens assembly includes a first lens **112**B and a third lens **112**C formed on the fiber connector **112**, and a second lens **1202** formed on the substrate **106**. As shown, light from the fiber cable **120** is transmitted along the fiber **112**A towards the first lens **112**B formed near the end of the fiber **112**A. The first lens **112**B directs light transmitted along the fiber **112**A towards the second lens **1202** on the PGL substrate **106**. The second lens **1202** on the PGL substrate **106** then reflects and re-direct the light back towards the third lens **112**C on the fiber connector **112**. The third lens **112**C finally reflects and re-directs the light to the optical structures **110** on the PGL substrate **106** for subsequent transmittance through the photonic engine **105**.

[0058] FIGS. **1-6** have described optical photonic devices having multiple optical structures formed on a substrate (e.g., glass substrate). The optical photonic device can include a photonic chip mounted on the photonic substrate and connected to multiple optical structures. The optical structures optically connect the photonic chip to a fiber connector configured to connect with an external fiber and operate to propagate light signals between the fiber connector and the photonic chip.

[0059] FIG. **7**A is a diagram of system **700**A, according to some embodiments. As shown in FIG. **7**A, system **700**A can include device **705**A including substrate **710**, at least one photonic integrated circuit (PIC) **720**, ball grid array **730** formed between substrate **710** and PIC **720**, and connection component **740**A integrated within device **705**A. More specifically, connection component **740**A is formed on PIC **720**. System **700**A further includes connection component **750**A coupled to optical fiber **760**.

[0060] In this illustrative example, connection component **740**A is a female connection component having a set of openings including opening **742**A. Connection component **750**A is a male connection component having a set of protrusions including protrusion **752**A. Each opening of the set of openings of connection component **740**A is designed to receive a respective protrusion of the set of protrusions of connection component **750**A. For example, opening **742**A is designed to receive protrusion **752**A.

[0061] System **700**A enables optical fiber-to-waveguide coupling on a plane parallel to an upper surface of substrate **710** (e.g., horizontal coupling). For example, connection component **740**A is attached to PIC **720** in a manner enables the connection component **750**A to be received along the plane parallel to the upper surface of substrate **710**.

[0062] FIG. **7**B is a diagram of a device or system **700**B, according to some embodiments. As shown in FIG. **7**B, system **700**B can include device **705**B including substrate **710**, at least one PIC **720**, ball grid array **730** formed between substrate **710** and PIC **720**, and connection component **740**B integrated within device **705**B. More specifically, connection component **740**B is formed on PIC **720**. System **700**B further includes connection component **750**B coupled to optical fiber **760**.

[0063] In this illustrative example, connection component **740**B is a male connection component having a set of protrusions including protrusion **742**B. Connection component **750**B is a female connection component having a set of openings including opening **752**B. Each opening of the set of openings of connection component **750**B is designed to receive a respective protrusion of the set of protrusions of connection component **740**B. For example, opening **752**B is designed to receive protrusion **742**B.

[0064] System **700**B enables optical fiber-to-waveguide coupling on a plane parallel to an upper surface of substrate **710** (e.g., horizontal coupling). For example, connection component **740**B is attached to PIC **720** in a manner enables the connection component **750**B to be received along the plane parallel to the upper surface of substrate **710**.

[0065] FIG. **7**C is a diagram of a device or system **700**C, according to some embodiments. As shown in FIG. **7**C, system **700**C can include device **705**C including substrate **710**, at least one PIC **720**, ball grid array **730** formed between substrate **710** and PIC **720**, and connection component **740**C integrated within device **705**C. More specifically, connection component **740**C is formed on PIC **720**. System **700**C further includes connection component **750**C coupled to optical fiber **760**.

[0066] In this illustrative example, connection component **740**C is a female connection component having a set of openings including opening **742**C. Connection component **750**C is a male connection component having a set of protrusions including protrusion **752**C. Each opening of the set of openings of connection component **740**C is designed to receive a respective protrusion of the set of protrusions of connection component **750**C. For example, opening **742**C is designed to receive protrusion **752**C.

[0067] System **700**C enables optical fiber-to-waveguide coupling on a plane perpendicular to an upper surface of substrate **710** (e.g., vertical coupling). For example, connection component **740**C is attached to PIC **720** in a manner enables the connection component **750**C to be received along the plane perpendicular to the upper surface of substrate **710**.

[0068] FIG. **7**D is a diagram of a device or system **700**D, according to some embodiments. As shown in FIG. **7**D, system **700**D can include device **705**D including substrate **710**, at least one PIC **720**, ball grid array **730** formed between substrate **710** and PIC **720**, and connection component **740**D integrated within device **705**D. More specifically, connection component **740**D is formed on PIC **720**. System **700**D further includes connection component **750**D coupled to optical fiber **760**.

[0069] In this illustrative example, connection component **740**D is a male connection component having a set of protrusions including protrusion **742**D. Connection component **750**D is a female connection component having a set of openings including opening **752**D. Each opening of the set of openings of connection component **750**D is designed to receive a respective protrusion of the set of protrusions of connection component **740**D. For example, opening **752**D is designed to receive protrusion **742**D.

[0070] System **700**D enables optical fiber-to-waveguide coupling on a plane perpendicular to an upper surface of substrate **710** (e.g., horizontal coupling). For example, connection component **740**D is attached to PIC **720** in a manner enables the connection component **750**D to be received along the plane perpendicular to the upper surface of substrate **710**.

[0071] FIG. **8**A is a diagram of a device or system **800**A, according to some embodiments. As shown in FIG. **8**A, system **800**A can include device **805**A including substrate **810**, multiple PICs including PIC **820-1** and **820-1**, multiple ball grid arrays formed between substrate **810** and respective ones of the PICs, including ball grid array **830-1** formed between substrate **810** and PIC **820-1** and ball grid array **830-2** formed between substrate **810** and PIC **820-2**, and connection component **840**A integrated within device **805**A. More specifically, connection component **840**A is formed on substrate **810**. System **800**A further includes connection component **850**A coupled to optical fiber **860**.

[0072] In this illustrative example, connection component **840**A is a female connection component having a set of openings including opening **842**A. Connection component **850**A is a male connection component having a set of protrusions including protrusion **852**A. Each opening of the set of openings of connection component **840**A is designed to receive a respective protrusion of the set of protrusions of connection component **850**A. For example, opening **842**A is designed to receive protrusion **852**A.

[0073] Similar to system **700**A, system **800**A enables optical fiber-to-waveguide coupling on a plane parallel to an upper surface of substrate **810** (e.g., horizontal coupling). For example, connection component **840**A is attached to substrate **810** in a manner enables the connection component **850**A to be received along the plane parallel to the upper surface of substrate **810**.

[0074] FIG. **8**B is a diagram of a device or system **800**B, according to some embodiments. As shown in FIG. **8**B, system **800**B can include device **805**B including substrate **810**, PICs including PIC **820-1** and PIC **820-2**, ball grid arrays including ball grid array **830-1** formed between substrate **810** and PIC **820-1** and ball grid array **830-2** formed between substrate **810** and PIC **820-2**, and connection component **840**B integrated within device **805**B. More specifically, connection component **840**B is formed on substrate **810**. System **800**B further includes connection component **850**B coupled to optical fiber **860**.

[0075] In this illustrative example, connection component **840**B is a male connection component having a set of protrusions including protrusion **842**B. Connection component **850**B is a female connection component having a set of openings including opening **852**B. Each opening of the set of openings of connection component **850**B is designed to receive a respective protrusion of the set of protrusions of connection component **840**B. For example, opening **852**B is designed to receive protrusion **842**B.

[0076] Similar to system **700**B, system **800**B enables optical fiber-to-waveguide coupling on a plane parallel to an upper surface of substrate **810** (e.g., horizontal coupling). For example, connection component **920** is attached to substrate **810** in a manner enables the connection component **850**B to be received along the plane parallel to the upper surface of substrate **810**.

[0077] FIG. **8**C is a diagram of a device or system **800**C, according to some embodiments. As shown in FIG. **8**C, system **800**C can include device **805**C including substrate **810**, PICs including PIC **820-1** and PIC **820-2**, ball grid arrays including ball grid array **830-1** formed between substrate **810** and PIC **820-1** and ball grid array **830-2** formed between substrate **810** and PIC **820-2**, and connection component **840**C integrated within device **805**C. More specifically, connection component **840**C is formed on substrate **810**. System **800**C further includes connection component **850**C coupled to optical fiber **860**.

[0078] In this illustrative example, connection component **840**C is a female connection component having a set of openings including opening **842**C. Connection component **850**C is a male connection component having a set of protrusions including protrusion **852**C. Each opening of the set of openings of connection component **840**C is designed to receive a respective protrusion of the set of protrusions of connection component **850**C. For example, opening **842**C is designed to receive protrusion **852**C.

[0079] Similar to system **700**C, system **800**C enables optical fiber-to-waveguide coupling on a plane perpendicular to an upper surface of substrate **810** (e.g., vertical coupling). For example, connection component **840**C is attached to substrate **810** in a manner enables the connection component **850**C to be received along the plane perpendicular to the upper surface of substrate **810**.

[0080] FIG. **8**D is a diagram of a device or system **800**D, according to some embodiments. As shown in FIG. **8**D, system **800**D can include device **805**D including substrate **810**, PICs including PIC **820-1** and PIC **820-2**, ball grid arrays including ball grid array **830-1** formed between

substrate **810** and PIC **820-1** and ball grid array **830-2** formed between substrate **810** and PIC **820-2**, and connection component **840**D integrated within device **805**D. More specifically, connection component **840**D is formed on substrate **810**. System **800**D further includes connection component **850**D coupled to optical fiber **860**.

[0081] In this illustrative example, connection component **840**D is a male connection component having a set of protrusions including protrusion **842**D. Connection component **850**D is a female connection component having a set of openings including opening **852**D. Each opening of the set of openings of connection component **850**D is designed to receive a respective protrusion of the set of protrusions of connection component **840**D. For example, opening **852**D is designed to receive protrusion **842**D.

[0082] System **800**D enables optical fiber-to-waveguide coupling on a plane perpendicular to an upper surface of substrate **810** (e.g., horizontal coupling). For example, connection component **840**D is attached to substrate **810** in a manner enables the connection component **850**D to be received along the plane perpendicular to the upper surface of substrate **810**.

[0083] FIG. **9** is a diagram of a device or system **900**, according to some embodiments. As shown in FIG. **9**, system **900** can include substrate **905** and connection component **910** formed on substrate **905**. Connection component **910** can include first portion of a cladding layer ("cladding layer portion") **912**, first portion of a collimator assembly ("collimator assembly portion") **914** formed in first portion of the cladding layer **912**, and waveguide **916** formed in cladding layer portion **912**. System **900** can further include connection component **920** corresponding to a detachable optical fiber component. Connection component **920** can include second portion of a cladding layer ("cladding layer portion") **922**, and second portion of the collimator assembly ("collimator assembly portion") **924** formed in cladding layer portion **912**. Connection component **920** can further include angle-cleaved optical fiber **926**. The collimator assembly can increase the alignment tolerance of connection component **920**. In some embodiments, collimator assembly portions **914** and **924** correspond to a pair of lenses forming a 4f optical system. In some embodiments, the collimator assembly is a meta-lens assembly. In some embodiments, the collimator assembly is a microlens assembly. In some embodiments, each lens has a diameter that ranges between about 30 μm to about 100 μm.

[0084] Optical signals **928** can travel through angle-cleaved optical fiber **926**, which can, upon incidence at the interface between angle-cleaved optical fiber **926** and the surrounding environment (e.g., air), be directed toward the collimator assembly. In some embodiments, distance "A" ranges between about 300 μm to about 500 μm. In some embodiments, distance "A" is about 400 μm. Optical signals can pass through the collimator assembly and can be coupled to waveguide **916**. Optical signals can be coupled to waveguide **916** with a small angle (e.g., less than or equal to about 20 degrees) to have a low impact on coupling loss. This can eliminate the need for a grating coupler or mirror alignment and can have relatively low loss and large 1 dB bandwidth in wavelength.

[0085] FIG. **10** is a diagram of a device or system **1000**, according to some embodiments. As shown in FIG. **10**, system **1000** can include substrate **1005** and connection component **1010** formed on substrate **1005**. Connection component **1010** can include cladding layer **1012** formed on substrate **1005**, trench **1013** formed at least through cladding layer **1012**, mirror **1014** formed (e.g., coated) on a sidewall of trench **1013**, and waveguide **222** formed within cladding layer **1012**.

[0086] Trench **1013** can have a triangular cross-sectional shape (e.g., right triangular cross-sectional shape), and mirror **1014** can be formed on an angled sidewall of trench **1013** (e.g., the sidewall corresponding to the hypotenuse of the right triangular cross-sectional shape). In some embodiments, trench **1013** is formed by using a dry etch process. Connection component **1010** can further include a stack including substrate **1016** and portion of a second cladding layer ("cladding layer portion") **1017** formed on substrate **1016**. Cladding layer **1012** and substrate **1016** can be bonded together by bonding layer **1019**. Portion of a collimator assembly ("collimator assembly portion") can be formed between substrate **1016** and cladding layer portion **1017**.

[0087] System **1000** can further include connection component **1020** corresponding to a detachable optical fiber connector including cleaved optical fiber **1022** formed on portion of the second cladding layer ("cladding layer portion") **1024**, and portion of the collimator assembly ("collimator assembly portion") **1026** formed within cladding layer portion **1024**. The collimator assembly can increase the alignment tolerance of connection component **1020**. In some embodiments, collimator assembly portions **1019** and **1026** correspond to a pair of lenses forming a 4f optical system. In some embodiments, the collimator assembly is a meta-lens assembly. In some embodiments, the collimator assembly is a microlens assembly. In some embodiments, each lens has a diameter that ranges between about 30 μm to about 100 μm.

[0088] Optical signals **1028** can travel through cleaved optical fiber **1022**, which can, upon incidence at the interface between cleaved optical fiber **1022** and cladding layer **1024**, be directed toward the collimator assembly. The collimator assembly can then direct optical signals **1028** toward mirror **1014**. Mirror **1014** can be designed to direct optical signals **1028** toward waveguide **222**. Optical signals **1028** can be coupled into waveguide **222** with a small angle (e.g., less than or equal to about 20 degrees) to have a low impact on coupling loss. This can eliminate the need for a grating coupler or mirror alignment and can have relatively low loss and large 1 dB bandwidth in wavelength.

[0089] In some embodiments, distance "B" ranges between about 10 μm to about 20 μm. In some embodiments, distance "B" is about 15 μm. In some embodiments, distance "C" ranges between about 600 μm to about 800 μm. In some embodiments, distance "C" is about 700 μm. In some embodiments, distance "D" ranges between about 600 μm to about 800 μm. In some embodiments, distance "D" is about 700 μm.

[0090] In some embodiments, the optical fiber **1022** is separated from the cladding layer portion **1024** by a gap. In some embodiments, the optical fiber **1022** is separated from the cladding layer portion **1024** by one or more layers.

[0091] FIG. **11** is a diagram of a device or system **1100**, according to some embodiments. As shown in FIG. **11**, system **1100** can include substrate **1105** and connection component **1110** formed on substrate **1105**. Connection component **1110** can include cladding layer **1111**, a set of waveguides include waveguides **1112-1** through **1112-3** formed within cladding layer **1111**, and mirror **1113** formed

within cladding layer **1111** and on substrate **1105**. More specifically, mirror **1113** can be formed within a trench formed within cladding layer **1111**. In some embodiments, mirror **1113** is an angled mirror having a triangular cross-sectional shape (e.g., right-triangular cross-sectional shape). Connection component **1110** can further include layer **1114** formed on cladding layer **1112**, and a first portion of a collimator assembly ("collimator assembly portion") **1115** formed in layer **1114**.

[0092] System **1100** can further include connection component **1120** corresponding to a detachable optical fiber component. Connection component **1120** can include cladding layer **1122**, second portion of the collimator assembly ("collimator assembly portion") **1124** formed in cladding layer **1122**, and optical fiber **1126** formed in cladding layer **1122**. Connection component **1120** can be attached to connection component **1110** via connectors **1130**. More specifically, connectors **1130** can enable connection component **1120** to be detached from connection component **1110**.

[0093] The collimator assembly can increase the alignment tolerance of connection component **920**. In some embodiments, collimator assembly portions **1115** and **1124** correspond to a pair of lenses forming a 4f optical system. In some embodiments, the collimator assembly is a metalens assembly. In some embodiments, the collimator assembly is a microlens assembly. In some embodiments, each lens has a diameter that ranges between about 30 μm to about 100 μm.

[0094] Optical signals **1132** can travel through the set of waveguides, which can, upon incidence upon mirror **1113**, be directed toward the collimator assembly. Optical signals **1132** can pass through the collimator assembly and can be coupled to optical fiber **1126**. Optical signals **1132** can be coupled to optical fiber **1126** with a small angle (e.g., less than or equal to about 20 degrees) to have a low impact on coupling loss. This can eliminate the need for a grating coupler or mirror alignment and can have relatively low loss and large 1 dB bandwidth in wavelength.

[0095] In some embodiments, distance "E" corresponding to the distance between substrate **1105** and waveguide **1112-3** ranges between about 4 μm to about 8 μm. In some embodiments, distance "E" is about 5 μm. In some embodiments, distance "F" corresponding to the distance between layer **1114** and waveguide **1112-2** ranges between about 4 μm to about 8 μm. In some embodiments, distance "F" is about 5 μm. In some embodiments, width "G" corresponding to the width of layer **1114** ranges between about 100 μm to about 500 μm. In some embodiments, each lens has a diameter that ranges between about 30 μm to about 100 μm.

[0096] FIG. **12** is a diagram of a device or system **1200**, according to some embodiments. As shown in FIG. **12**, system **1200** can include substrate **1205** and connection component **1210** formed on substrate **1205**. Connection component **1110** can include cladding layer **1212**, waveguide **1214** formed within cladding layer **1212**, and mirror **1216** formed within cladding layer **1212**. More specifically, mirror **1216** can be formed within a trench formed within cladding layer **1212**. In some embodiments, mirror **1216** is a concave mirror. In some embodiments, connection component **1210** further includes spacer **1218** formed on cladding layer **1212**.

[0097] System **1200** can further include connection component **1220** corresponding to a detachable optical fiber component. Connection component **1220** can include cladding layer **1222**, mirror **1224** formed in cladding layer **1222**, and optical fiber **1226** formed in cladding layer **1222**. More specifically, mirror **1224** can be formed within a trench formed within cladding layer **1222**. In some embodiments, mirror **1224** is a concave mirror. Connection component **1220** can be attached to connection component **1210** via connectors **1230**. More specifically, connectors **1230** can enable connection component **1220** to be detached from connection component **1210**. In some embodiments, connectors **1230** are attached to spacer **1218**. In some embodiments, connectors **1230** are attached to cladding layer **1212**.

[0098] Optical signals **1232** can travel through waveguide **1214**, which can, upon incidence upon mirror **1216**, be directed toward mirror **1224**. Upon incidence upon mirror **1224**, optical signals **1232** can be coupled to optical fiber **1226**. Optical signals **1232** can be coupled to optical fiber **1226** with a small angle (e.g., less than or equal to about 20 degrees) to have a low impact on coupling loss. This can eliminate the need for a grating coupler or mirror alignment and can have relatively low loss and large 1 dB bandwidth in wavelength.

[0099] In some embodiments, width "H" corresponding to the width of collimator layer **1212** ranges between about 20 μm to about 40 μm. In some embodiments, width "H" is about 30 μm. In some embodiments, width "I" corresponding to the width of spacer **1218** ranges between about 200 μm to about 400 μm. In some embodiments, width "I" is about 300 μm.

[0100] FIG. **13**A is a diagram of a device or system **1300**A, according to some embodiments. As shown in FIG. **13**A, system **1300**A can include substrate **1305** and connection component **1310**A formed on substrate **1305**. Connection component **1310**A can include cladding layer **1312**A formed on substrate **1305**, trench **1313**A formed at least through cladding layer **1312**, mirror **1314**A formed (e.g., coated) on a sidewall of trench **1313**A, and waveguide **1315**A formed within cladding layer **1312**A. Trench **1313**A can have a triangular cross-sectional shape (e.g., right triangular cross-sectional shape), and mirror **1314**A can be formed on an angled sidewall of trench **1313**A (e.g., the sidewall corresponding to the hypotenuse of the right triangular cross-sectional shape). In some embodiments, trench **1313**A is formed by using a dry etch process. Connection component **1310**A can further include microlens **1316**A which forms a collimator assembly portion. In some embodiments, trench **1313**A is filled with an index matched material (e.g., that matches to the index of cladding layer **1312**). The Index matched material may be, for example SiOx, SiN, and/or another material.

[0101] System **1300**A can further include connection component **1320** corresponding to a detachable optical fiber connector including cleaved optical fiber **1322** formed on microlens **1324**. Microlens **1324** can form another collimator assembly portion. The collimator assembly can increase the alignment tolerance of connection component **1320**. Accordingly, in these embodiments, the collimator assembly is a microlens assembly. In some embodiments, each lens has a diameter that ranges between about 30 μm to about 100 μm. Connection components **1310**A and **1320** can be attached using mechanical connectors **1330**A (e.g., pins or tubes).

[0102] Optical signals **1328** can travel through cleaved optical fiber **1322** toward the collimator assembly. The collimator assembly can then direct optical signals **1328**

toward mirror **1314**A. Mirror **1314**A can be designed to direct optical signals **1328** toward waveguide **1315**. Optical signals **1328** can be coupled into waveguide **1315** with a small angle (e.g., less than or equal to about 20 degrees) to have a low impact on coupling loss. This can eliminate the need for a grating coupler or mirror alignment and can have relatively low loss and large 1 dB bandwidth in wavelength.

[0103] In some embodiments, at least one of the microlens **1316**A or **1324** is a freeform microlens. For example, at least one of the microlens **1316**A or **1324** can be a cylindrical lens if the waveguide mode is elliptical. A freeform microlens can be designed with parametric surfaces, to convert arbitrary mode shape from waveguide to a symmetric circular shape to match the mode at the fiber end.

[0104] In some embodiments, distance "J" corresponding to the height of the trench **1313**A ranges between about 5 μm to about 15 μm. In some embodiments, distance "J" is about 10 μm. In some embodiments, distance "K" corresponding to the distance between the apex of microlens **1316**A and the surface of cladding layer **1312**A ranges between about 200 μm to about 600 μm. In some embodiments, distance "K" is about 400 μm. In some embodiments, distance "L" corresponding to the distance between the apex of microlens **1324** and cleaved optical fiber **1322** ranges between about 200 μm to about 600 μm. In some embodiments, distance "L" is about 400 μm.

[0105] In some embodiments, the optical fiber **1322** is separated from the microlens **1324** by a gap. In some embodiments, the optical fiber **1322** is separated from the microlens **1324** by one or more layers.

[0106] FIG. **13**B is a diagram of a device or system **1300**B, according to some embodiments. As shown in FIG. **13**B, system **1300**B can include substrate **1305** and connection component **1310**B formed on substrate **1305**. Connection component **1310**B can include cladding layer **1312**B formed on substrate **1305**, mirror **1314**B formed within cladding layer **1312**B, and waveguide **1315**A formed within cladding layer **1312**B. Connection component **1310**B can further include metalens array or stack **1317**B which forms a collimator assembly portion. In some embodiments, mirror **1314**B is formed in a trench formed in cladding layer **1312**B, and the trench is then backfilled with an index matched material that is index matched to the cladding layer **1312**B after formation of the mirror **1314**B.

[0107] System **1300**B can further include connection component **1320** corresponding to a detachable optical fiber connector including cleaved optical fiber **1322** formed on microlens **1324**, as described above with reference to FIG. **13**A. Microlens **1324** can form another collimator assembly portion. The metalens array **1317**B can be used to achieve lithography-defined overlay accuracy, broadband operation over the entire original band (O-band) (e.g., wavelengths ranging from about 1260 nanometers (nm) to about 1360 nm), and high flexibility of beam shaping. A metalens can be made of any suitable material. Examples of suitable materials include silicon (Si), titanium oxide (TiO_2), etc. The collimator assembly can increase the alignment tolerance of connection component **1320**. Accordingly, in these embodiments, the collimator assembly is a hybrid microlens-metalens assembly. In some embodiments, each lens has a diameter that ranges between about 30 μm to about 100 μm. Connection components **1310**B and **1320** can be attached using mechanical connectors **1330**B (e.g., pins or tubes).

[0108] Optical signals **1328** can travel through cleaved optical fiber **1322** toward the collimator assembly. The collimator assembly can then direct optical signals **1328** toward mirror **1314**A. Mirror **1314**B can be designed to direct optical signals **1328** toward waveguide **1315**. Optical signals **1328** can be coupled into waveguide **1315** with a small angle (e.g., less than or equal to about 20 degrees) to have a low impact on coupling loss. This can eliminate the need for a grating coupler or mirror alignment and can have relatively low loss and large 1 dB bandwidth in wavelength. In some embodiments, the microlens **1324** is a freeform microlens. For example, microlens **1324** can be a cylindrical lens if the waveguide mode is elliptical.

[0109] In some embodiments, distance "M" corresponding to the height of the mirror **1314**B is less than or equal to about 10 μm. In some embodiments, the distance "M" is less than or equal to about 6 μm. The distance "L" is similar to the distance "L" described above with reference to FIG. **13**A.

[0110] In some embodiments, the optical fiber **1322** is separated from the microlens **1324** by a gap. In some embodiments, the optical fiber **1322** is separated from the microlens **1324** by one or more layers.

[0111] FIG. **13**C is a diagram of a device or system **1300**C, according to some embodiments. As shown in FIG. **13**B, system **1300**C can include substrate **1305** and connection component **1310**C formed on substrate **1305**. Connection component **1310**C can include cladding layer **1312**C formed on substrate **1305**, mirror **1314**C formed within cladding layer **1312**C, and waveguide **1315**A formed within cladding layer **1312**C. Connection component **1310**C can further include microlens **1316**C and metalens array or stack **1317**C which forms a collimator assembly portion. The metalens array **1317**C can be used to slow down the divergence of light.

[0112] System **1300**C can further include connection component **1320** corresponding to a detachable optical fiber connector including cleaved optical fiber **1322** formed on microlens **1324**, as described above with reference to FIGS. **13**A-**13**B. Microlens **1324** can form another collimator assembly portion. The collimator assembly can increase the alignment tolerance of connection component **1320**. Accordingly, in these embodiments, the collimator assembly is a hybrid microlens-metalens assembly. In some embodiments, each lens has a diameter that ranges between about 30 μm to about 100 μm. Connection components **1310**C and **1320** can be attached using mechanical connectors **1330**C (e.g., pins or tubes).

[0113] Optical signals **1328** can travel through cleaved optical fiber **1322** toward the collimator assembly. The collimator assembly can then direct optical signals **1328** toward mirror **1314**A. Mirror **1314**C can be designed to direct optical signals **1328** toward waveguide **1315**. Optical signals **1328** can be coupled into waveguide **1315** with a small angle (e.g., less than or equal to about 20 degrees) to have a low impact on coupling loss. This can eliminate the need for a grating coupler or mirror alignment and can have relatively low loss and large 1 dB bandwidth in wavelength.

[0114] In some embodiments, at least one of the microlens **1316**C or **1324** is a freeform microlens. For example, at least one of the microlens **1316**C or **1324** can be a cylindrical lens if the waveguide mode is elliptical. The distances "M", "K" and "L" are similar to the distances "K" and "L" described above with reference to FIGS. **13**A-**13**B.

[0115] In some embodiments, the optical fiber **1322** is separated from the microlens **1324** by a gap. In some embodiments, the optical fiber **1322** is separated from the microlens **1324** by one or more layers.

[0116] FIG. **14** is a flowchart of an example method to enable detachable optical fiber-to-waveguide coupling with standard optical fiber connector types, according to some embodiments.

[0117] At block **1410**, a base structure of a device is received. Receiving the base structure can include forming at least one PIC on a substrate. For example, forming the at least one PIC on the substrate can include forming a ball grid array on the substrate, and forming the at least one PIC on the ball grid array.

[0118] At block **1420**, a first connection component is formed on the base structure and, at block **1430**, the first connection component is mated to a second connection component coupled to an optical fiber. In some embodiments, forming the first connection component on the base structure includes attaching the first connection component to the at least one PIC. In some embodiments, forming the first connection component on the base structure includes attaching the first connection component to the substrate. In some embodiments, the first connection component is a female component having a set of openings and the second connection component is a male component having a set of protrusions, where each protrusion is configured to mate with a respective opening of the set of openings. In some embodiments, the first connection component is a male component having a set of protrusions and the second connection component is a female component having a set of openings, where each protrusion of the set of protrusions is configured to mate with a respective opening of the set of openings.

[0119] In some embodiments, the first connection component corresponds to connection component **910** of FIG. **9** and the second connection component corresponds to connection component **920** of FIG. **9**. In some embodiments, the first connection component corresponds to connection component **1010** of FIG. **10** and the second connection component corresponds to connection component **1020** of FIG. **10**. In some embodiments, the first connection component corresponds to connection component **1110** of FIG. **11** and the second connection component corresponds to connection component **1120** of FIG. **11**. In some embodiments, the first connection component corresponds to connection component **1210** of FIG. **12** and the second connection component corresponds to connection component **1220** of FIG. **12**. In some embodiments, the first connection component corresponds to connection component **1310**A of FIG. **13**A and the second connection component corresponds to connection component **1320** of FIG. **13**A. In some embodiments, the first connection component corresponds to connection component **1310**B of FIG. **13**B and the second connection component corresponds to connection component **1320** of FIG. **13**B. In some embodiments, the first connection component corresponds to connection component **1310**C of FIG. **13**C and the second connection component corresponds to connection component **1320** of FIG. **13**C. Further details regarding blocks **1410-1430** are described above with reference to FIGS. **1-13**C.

[0120] 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.

[0121] 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.

[0122] 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.

[0123] 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."

[0124] 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.

[0125] 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, con-

currently with other operations. In another embodiment, instructions or sub-operations of distinct operations may be in an intermittent and/or alternating manner.

[0126] 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:

a first connection component comprising a waveguide and a mirror formed on a base structure, the base structure comprising at least one photonic integrated circuit (PIC) formed on a substrate; and

a detachable second connection component coupled to an optical fiber, the detachable second connection component being configured to mate with the first connection component to enable optical signal coupling between the optical fiber and the waveguide;

wherein the mirror is configured to at least one of: reflect a first optical signal received from the waveguide to the optical fiber, or reflect a second optical signal received from the optical fiber to the waveguide.

2. The system of claim **1**, wherein the first connection component is formed on the at least one PIC.

3. The system of claim **1**, wherein the first connection component is formed on the substrate.

4. The system of claim **1**, wherein the first connection component is a female connection component having a set of openings, wherein the detachable second connection component is a male connection component having a set of protrusions, and wherein each opening of the set of openings is designed to receive a respective protrusion of the set of protrusions.

5. The system of claim **1**, wherein the first connection component is a male connection component having a set of protrusions, wherein the detachable second connection component is a female connection component having a set of openings, and wherein each opening of the set of openings is designed to receive a respective protrusion of the set of protrusions.

6. The system of claim **1**, wherein at least one of the first connection component or the detachable second connection component comprises a microlens configured to expand and collimate at least one of: the first optical signal emitted from the waveguide into a first light beam having a diameter of approximately 30-150 micrometers, or the second optical signal emitted from the optical fiber into a second light beam having a diameter of approximately 30-150 micrometers.

7. The system of claim **6**, wherein the first connection component and the detachable second connection component are configured to enable a 1-5 micrometer alignment accuracy between the first connection component and the detachable second connection component.

8. The system of claim **1**, wherein at least one of the first connection component or the detachable second connection component comprises a metalens.

9. The system of claim **1**, wherein the first connection component comprises a first microlens, and wherein the detachable second connection component comprises a second microlens and a metalens array.

10. The system of claim **1**, wherein the optical fiber is approximately orthogonal to the waveguide.

11. A method comprising:

receiving a base structure comprising at least one photonic integrated circuit (PIC) formed on a substrate;

forming, on the base structure, a first connection component comprising a waveguide and a mirror; and

mating the first connection component to a detachable second connection component coupled to an optical fiber to enable optical signal coupling between the optical fiber and the waveguide;

wherein the mirror is configured to at least one of: reflect a first optical signal received from the waveguide to the optical fiber, or reflect a second optical signal received from the optical fiber to the waveguide.

12. The method of claim **11**, wherein the first connection component is formed on the at least one PIC.

13. The method of claim **11**, wherein the first connection component is formed on the substrate.

14. The method of claim **11**, wherein the first connection component is a female connection component having a set of openings, wherein the detachable second connection component is a male connection component having a set of protrusions, and wherein each opening of the set of openings is designed to receive a respective protrusion of the set of protrusions.

15. The method of claim **11**, wherein the first connection component is a male connection component having a set of protrusions, wherein the detachable second connection component is a female connection component having a set of openings, and wherein each opening of the set of openings is designed to receive a respective protrusion of the set of protrusions.

16. The method of claim **11**, wherein at least one of the first connection component or the detachable second connection component comprises a microlens configured to expand and collimate at least one of: the first optical signal emitted from the waveguide into a first light beam having a diameter of approximately 30-150 micrometers, or the second optical signal emitted from the optical fiber into a second light beam having a diameter of approximately 30-150 micrometers.

17. The method of claim **11**, wherein the first connection component and the detachable second connection component are mated with an alignment accuracy of 1-5 micrometers.

18. The method of claim **11**, wherein at least one of the first connection component or the detachable second connection component comprises a metalens.

19. The method of claim **11**, wherein the first connection component comprises a first microlens, and wherein the detachable second connection component comprises a second microlens and a metalens array.

20. The method of claim **11**, wherein the first connection component comprises a mirror to reflect an optical signal received from the waveguide or the optical fiber to the optical fiber or the waveguide, respectively.

* * * * *