

INTEGRATED OPTICAL CIRCUIT SWITCH DEVICES AND METHODS OF FABRICATING SAME

INCORPORATION BY REFERENCE TO ANY PRIORITY APPLICATIONS

[0001] This application claims benefit under 35 U.S.C. §119(e) of U.S. Provisional Patent Application No. 63/511427, entitled “MICRO-ELECTROMECHANICAL SYSTEM OPTICAL CIRCUIT SWITCH FABRICATED ON TWO WAFERS,” filed on June 30, 2023, and U.S. Provisional Patent Application No. 63/562179, entitled “INTEGRATED OPTICAL CIRCUIT SWITCH DEVICES AND METHODS OF FABRICATING SAME,” filed on March 6, 2024, both of which are incorporated herein by reference in their entirety.

BACKGROUND

Field

[0002] The present disclosure generally relates to optical switches used for routing optical signals in photonic systems and circuits, and more particularly to integrated optical circuit switches comprising electromechanically actuated optical switches.

Description of the Related Art

[0003] Performing data processing and data transport tasks in an optical domain can significantly increase data transmission and processing rates compared to electronic systems. One of the important tasks in most computing or communication systems is controlling signal paths within a network of signal channels. A switching circuit can include reconfigurable interconnections that controllably transfer signals between different channels. Optical switching circuits that provide reconfigurable optical interconnections between a plurality of optical waveguides are important building blocks in most optical processing and communication systems and their performance advantages can have a significant impact on these systems.

SUMMARY

[0004] In some aspects, the techniques described herein relate to an integrated optical circuit (IOC) including: a first waveguide layer having formed therein a first bus optical waveguide; a second waveguide layer having formed therein a second bus optical waveguide; an optical switch including a shunt waveguide disposed in a gap vertically between the first and second bus optical waveguide layers and configured to moveably couple the first bus optical waveguide and the second bus optical waveguide upon activation; and a pair of optical alignment structures formed in the first and second waveguide layers, wherein the optical alignment structures are optically aligned within a predetermined tolerance to correspondingly align the first and second waveguide layers and the optical switch within a predetermined tolerance such that when activated, the shunt waveguide optically couples first and second bus optical waveguides to redirect light therebetween.

[0005] In some aspects, the techniques described herein relate to a method of aligning two wafers including integrated photonic devices, the method including: providing a first wafer, the first wafer including: a first waveguide layer having formed therein a first bus optical waveguide, an optical switch structure including a shunt waveguide configured to moveably optically couple the first bus optical waveguide to a second bus optical waveguide upon activation to redirect light between the first and second bus optical waveguides, and a first one of a pair of optical alignment structures including a first waveguiding structure; providing a second wafer, the second wafer including: a second waveguide layer having formed therein the second bus optical waveguide, and a second one of the pair of optical alignment structures including a second waveguiding structure; providing optical input power to the first waveguiding structure of the first one of the pair of optical alignment structures; positioning the second wafer with respect to the first wafer such that the second waveguiding structure is positioned above the first waveguiding structure; measuring an output optical power output by the second waveguiding structure as a result of optical coupling between the first and second waveguiding structures; aligning the first wafer with respect to the second wafer based on the measured output optical power; and wherein the measured output optical power directly correlates to an optical coupling strength between the first and second optical waveguides, when the optical switch structure is activated.

[0006] In some aspects, the techniques described herein relate to an integrated optical circuit (IOC) including: a first waveguide layer having formed therein a first bus optical waveguide; a second waveguide layer having formed therein a second bus optical waveguide; an optical switch including a shunt waveguide disposed in a gap vertically between the first and second bus optical waveguide layers and configured to moveably couple the first bus optical waveguide and the second bus optical waveguide upon activation; and a pair of physical alignment structures formed on the first and second waveguide layers, wherein the physical alignment structures are physically coupled to align the first and second waveguide layers and the optical switch within a predetermined tolerance such that when activated, the shunt waveguide optically couples first and second bus optical waveguides to redirect light therebetween.

[0007] In some aspects, the techniques described herein relate to a method of aligning two wafers including integrated photonic devices, the method including: providing a first wafer, the first wafer including: a first waveguide layer having formed therein a first bus optical waveguide, an optical switch structure including a shunt waveguide configured to moveably optically couple the first bus optical waveguide to a second bus optical waveguide upon activation to redirect light between the first and second bus optical waveguides, and a first physical alignment structure of a pair of physical alignment structures; providing a second wafer, the second wafer including: a second waveguide layer having formed therein the second bus optical waveguide, and a second physical alignment structure of the pair of physical alignment structures, the second physical alignment structure configured to physically couple to the first physical alignment structure; aligning the first and second wafers laterally to align the first physical alignment structure over the second physical alignment structure within a predetermined tolerance; vertically engaging the first and second physical alignment structures such that, when activated, the shunt waveguide optically couples first and second bus optical waveguides to redirect light therebetween.

[0008] In some aspects, the techniques described herein relate to a method of aligning two wafers including integrated photonic devices, the method including: providing a first wafer, the first wafer including: a first waveguide layer having formed therein a first bus optical waveguide, an optical switch structure including a shunt waveguide configured to moveably optically couple the first bus optical waveguide to a second bus optical waveguide

upon activation to redirect light between the first and second bus optical waveguides, and a first physical alignment structure of a pair of physical alignment structures; providing a second wafer, the second wafer including: a second waveguide layer having formed therein the second bus optical waveguide, and a second physical alignment structure of the pair of physical alignment structures, the second physical alignment structure configured to physically couple to the first physical alignment structure; providing a microbead between the first and second physical alignment structures to mechanically link first and second physical alignment structures; aligning the first and second wafers laterally to align the first physical alignment structure over the second physical alignment structure within a predetermined tolerance; vertically engaging the first and second physical alignment structures via the microbead such that, when activated, the shunt waveguide optically couples first and second bus optical waveguides to redirect light therebetween.

[0009] In some aspects, the techniques described herein relate to an integrated optical circuit (IOC) including: a first waveguide layer formed on a substrate, the first waveguide layer having formed therein a first bus optical waveguide; a second waveguide layer having formed therein a second bus optical waveguide; an optical switch including a shunt waveguide disposed in a gap vertically between the first and second bus optical waveguide layers and configured to moveably optically couple the first bus optical waveguide and the second bus optical waveguide upon activation to redirect light between the first and second bus optical waveguides; and a plurality of vertical vias serving as mechanical anchors and electrical connections between the first and second waveguide layers to fixedly suspend the second waveguide layer above the first waveguide layer, the vertical vias formed of a material that is etch-selective to a sacrificial material removed from the gap during fabrication.

[0010] In some aspects, the techniques described herein relate to a method of fabricating an integrated optical circuit (IOC) device, the method including: fabricating a first wafer including: lithographically patterning to form a first bus optical waveguide extending within a first waveguide layer on a front side of a first substrate, and forming on the first substrate an optical switch structure including a shunt waveguide at least partly fixedly buried in a sacrificial material; fabricating a second wafer including lithographically patterning to form a second optical bus waveguide extending within a second waveguide layer on a front side of a second substrate; bonding the front surface of the second wafer to the front surface of

the first wafer; removing the second substrate; forming a plurality of vertical vias through the second waveguide layer and further through the sacrificial material, the vertical vias serving as mechanical anchors and electrical connections between the first and second waveguide layers; selectively removing the sacrificial material to release the shunt waveguide to configure the shunt waveguide to moveably optically couple the first bus optical waveguide and the second bus optical waveguide upon activation to redirect light between the first and second bus optical waveguides.

[0011] In some aspects, the techniques described herein relate to an integrated optical circuit (IOC) device including: a first waveguide layer formed on a first substrate, the first waveguide layer having formed therein a first bus optical waveguide; a second waveguide layer formed on a second substrate, the second waveguide layer having formed therein a second bus optical waveguide; an optical switch including a shunt waveguide disposed in a gap vertically between the first and second bus optical waveguide layers and configured to moveably optically couple the first bus optical waveguide and the second bus optical waveguide upon activation to redirect light between the first and second bus optical waveguides a plurality of mechanical stoppers vertically extending between the first and second wafers, wherein each mechanical stopper has a first mechanical stopper portion formed on the first substrate and a second mechanical stopper portion formed on the second substrate, wherein the second wafer is bonded to the first wafer using the mechanical stoppers such that the first bus optical waveguide is vertically separated from the second bus optical waveguide by a distance defined by the mechanical stopper.

[0012] In some aspects, the techniques described herein relate to a method of fabricating an integrated optical circuit switching (OCS) device having at least one optical switching cell, the method including: fabricating a first wafer including: lithographically patterning to form a first bus optical waveguide extending within a first waveguide layer on a front side of a first substrate, and forming on the first substrate an optical switch structure including a shunt waveguide at least partly fixedly buried in a sacrificial material; fabricating a second wafer including: lithographically patterning to form a second optical bus waveguide extending within a second waveguide layer on a front side of a second substrate; forming a plurality of mechanical stoppers each having a first portion formed on the first substrate and a second portion formed on the second substrate; selectively removing the sacrificial material to

release the shunt waveguide; bonding the second wafer to the first wafer by contacting at least the first portions of the mechanical stoppers to corresponding second portions of the mechanical stoppers such that the first bus optical waveguide is vertically separated from the second bus optical waveguide by a distance defined by the mechanical stoppers, and that the shunt waveguide is configured to moveably optically couple the first bus optical waveguide and the second bus optical waveguide upon activation to redirect light between the first and second bus optical waveguides.

[0013] In some aspects, the techniques described herein relate to an optical switching cell, including: a first waveguide layer having formed therein a first bus optical waveguide; a second waveguide layer having formed therein a second bus optical waveguide; an optical switch including a shunt waveguide disposed in a vertical gap between the first and second bus optical waveguide layers and configured to moveably couple the first bus optical waveguide and the second bus optical waveguide upon activation; and one or more microelectromechanical systems (MEMS) actuators configured to, upon actuation, mechanically move one or both end regions of the shunt waveguide to cause the first bus optical waveguide to be optically coupled with the second bus optical waveguide.

[0014] In some aspects, the techniques described herein relate to an integrated optical circuit including: a first plurality of bus optical waveguides formed over a substrate and terminating with a first plurality of optical ports; a second plurality of bus optical waveguides formed over the substrate; a plurality optical switches including a plurality of shunt optical waveguides configured to redirect light between individual optical bus waveguides of the first plurality of bus optical waveguides to individual optical bus waveguides of the second plurality of bus optical waveguides, upon being activated by activation signals; and a plurality of sensors disposed on the substrate and configured to generate a plurality of sensor signals indicating ON and OFF states of the plurality of optical switches.

[0015] In some aspects, the techniques described herein relate to an integrated optical circuit including: a first bus optical waveguide formed over a substrate; a second bus optical waveguide formed over the substrate; a recovery waveguide formed over the substrate; a primary optical switch including a first shunt optical waveguide configured to moveably optically couple the first bus optical waveguide and the second bus optical waveguide upon activation by a first activation signal to redirect light between the first and second bus optical

waveguides; a first recovery optical switch including a second shunt optical waveguide configured to moveably optically couple the first bus optical waveguide and the recovery waveguide upon being activated by a second activation signal to redirect light between the first bus optical waveguide and the recovery waveguide section; and a second recovery optical switch including a third shunt optical waveguide configured to moveably optically couple the second bus optical waveguide and the recovery waveguide upon being activated by a second activation signal to redirect light between the second bus optical waveguide and the recovery waveguide section, wherein the recovery waveguide is configured to couple the first and second bus optical waveguides when the second and third optical switches are activated.

[0016] In some aspects, the techniques described herein relate to an integrated optical circuit including: a first plurality of optical waveguides longitudinally extending on a substrate and terminating near an edge of a substrate; a first edge optical coupler formed on the substrate and configured to optically couple an optical fiber to a first optical waveguide of the first plurality of optical waveguides, the first edge optical coupler including a tapered waveguide longitudinally extending from an end of the first optical waveguide to the edge of the substrate, wherein a lateral width of the tapered waveguide decreases from the end of the first optical waveguide to the edge of the substrate, and wherein a region of the substrate below the tapered waveguide is removed to form a slit under the tapered waveguide.

[0017] In some aspects, the techniques described herein relate to a edge coupler interposer including: a first array of waveguide facets at first periodic positions along a lateral direction, a first longitudinal position and a common vertical position; and second and third arrays of waveguide facets, at a second longitudinal position, wherein the second and third arrays of waveguide facets are vertically separated and form an array of vertically separated waveguide facet pairs at second periodic positions along the lateral direction, wherein a first lateral pitch of the first array of waveguide facets is smaller than a second lateral pitch of the second array of waveguide facets; wherein first and second waveguide facets of the first array of waveguide facets are optically coupled to different waveguide facets of a vertically separated waveguide facet pair of the array of vertically separated waveguide facet pairs, respectively.

BRIEF DESCRIPTION OF THE DRAWINGS

[0018] Figure 1 schematically illustrates an optical switch network comprising a plurality of optical waveguides that are controllably interconnected using a plurality of switching cells.

[0019] Figure 2A schematically illustrates a top view of an example integrated optical circuit switch (IOCS) device including an optical switch matrix and two groups of bus optical waveguides optically connected to optical ports at an edge of the IOCS device.

[0020] Figure 2B schematically illustrates a top view of an example IOCS device including an optical switch matrix and two groups of bus optical waveguides optically connected to optical ports at opposite edges of the IOCS device.

[0021] Figure 2C schematically illustrates a top view of an example IOCS device including an optical switch matrix and two groups of bus optical waveguides connected to a group of optical ports at an edge of the IOCS device.

[0022] Figure 2D schematically illustrates a top view of an example IOCS device including an optical switch matrix and two groups of bus optical waveguides connected to optical ports at opposite edges of the IOCS device.

[0023] Figure 3A schematically illustrates top view and two cross-sectional side views of an example optical switching cell of the IOCS devices shown in Figures 2A-2D in an OFF state.

[0024] Figures 3B-3C schematically illustrate closeup views of the end regions of the shunt waveguide of the optical switching cell shown in Figure 3A and the corresponding microelectromechanical systems (MEMS) actuator and flexible support structures.

[0025] Figure 4 schematically illustrates top view and two cross-sectional side views of the optical switching cell shown in Figure 3A in an ON state.

[0026] Figure 5A schematically illustrates a vertical cross-sectional side view of the optical switching cell shown in Figure 3A along a curved cut surface A'A showing the corresponding portions of the bus optical waveguides, the shunt waveguide, and the MEMS actuators that control the end regions of the shunt waveguide.

[0027] Figure 5B schematically illustrate a closeup view of an end region of the shunt waveguide of the optical switching cell shown in Figure 5B and the corresponding MEMS actuators.

[0028] Figures 6A-6B schematically illustrate two cross-sectional side views of a single switching cell of an example IOCS device according to a first embodiment described herein. The two cross-sectional side views are rotated by 90 degrees with respect to each other.

[0029] Figures 6C is a flow diagram of an example process for fabricating the IOCS device shown in Figure 6A-6B according to some embodiments disclosed herein.

[0030] Figures 7A-7B schematically illustrate two cross-sectional side views of a single switching cell of an example IOCS device according to a second embodiment described herein. The two cross-sectional side views are rotated by 90 degrees with respect to each other.

[0031] Figure 7C is a flow diagram of an example process for fabricating the IOCS device shown in Figure 7A-7B according to some embodiments disclosed herein.

[0032] Figures 8A-8B schematically illustrates top views of first and second substrates used to fabricate an example IOCS device having optical ports formed on the second substrate and inter-layer couplers that optically connect the bus optical waveguides of the first substrate to the optical ports the second substrate.

[0033] Figures 8C-8D schematically illustrates two cross-sectional side views of the example IOCS formed using the first and second substrates shown in Figures 8A-8B. The two cross-sectional side views are rotated by 90 degrees with respect to each other.

[0034] Figures 9A-9B schematically illustrates top views of the first and second substrates used to fabricate an example IOCS device having optical ports formed on the first substrate and inter-layer couplers that optically connect the bus optical waveguides of the second substrate to the optical ports on the first substrate.

[0035] Figures 9C-9D schematically illustrates two cross-sectional side views of the example IOCS formed using the first and second substrates shown in Figures 9A-9B. The two cross-sectional side views are rotated by 90 degrees with respect to each other.

[0036] Figures 10A-10B schematically illustrates top views of the first (A) and second (B) substrates used to fabricate an example IOCS device having a first group of optical ports formed on the first substrate and a second group of optical ports formed on the second substrate, each group of optical ports connected to the waveguides on the respective substrate without any inter-layer coupler.

[0037] Figures 10C-10D schematically illustrates two cross-sectional side views of the example IOCS formed using the first and second substrates shown in Figures 10A-10B. The two cross-sectional side views are rotated by 90 degrees with respect to each other.

[0038] Figures 11A-11C schematically illustrate a top view (A), a side view (B), and a perspective view (C) of an example tapered waveguide inter-layer coupler.

[0039] Figures 12A-12B schematically illustrates a top view of a first substrate (A) or wafer comprising first portions of active alignments structures and a second substrate (B) or wafer comprising second portions of the active alignment structures.

[0040] Figure 12C schematically illustrates a see-through top view of the IOCS device formed by overlapping the first and second substrates or wafers when the active alignment structures on the two wafers are aligned to increase or maximize the optical power transmitted via one or more pairs of the active alignment structures.

[0041] Figures 13A-13C schematically illustrate perspective views of three pairs of substrates (or wafers) having self-alignment structures comprising protrusions and opening having different shapes.

[0042] Figures 13D-13F schematically illustrate see-through top views of the three pairs of substrates shown in Figures 13A-13C respectively when the two substrates of each pair are overlapped and the portions of the self-alignment structures on the first and second substrates are engaged.

[0043] Figure 13G and Figure 13H schematically illustrate close-up cross-sectional side views of alignment structures of the pairs of substrates shown in Figure 13A and 13C, respectively, when the two substrates of each pair are overlapped and the portions of the self-alignment structures on the first and second substrates are engaged.

[0044] Figures 14A-14C schematically illustrate perspective views of three pairs of substrates (or wafers) having self-alignment structures comprising opening (or holes) having different shapes, where the openings on the first substrate are configured to be mechanically coupled to the opening on the second substrate by microbeads.

[0045] Figures 14D -14F schematically illustrate see-through top views of the three pairs of substrates shown in Figures 14A-14C, respectively, when the two substrates of each pair are overlapped and the portions of the self-alignment structures on the first and second substrates are and mechanically coupled via the microbeads.

[0046] Figure 14G schematically illustrates a close-up cross-sectional side view of an alignment structure of any one of the three pairs of substrates shown in Figure 14A-14C when the two substrates of each pair are overlapped and the portions of the self-alignment structures on the first and second substrates are mechanically coupled by a microbead.

[0047] Figure 15A schematically illustrates a perspective view of a pairs of substrates (or wafers) having self-alignment structures comprising cylindrical protrusions and holes.

[0048] Figure 15B schematically illustrates a see-through top view of the pairs of substrates shown in Figure 15A when the two substrates overlapped and the self-alignment structures on the first and second substrates are engaged.

[0049] Figure 15C schematically illustrates a side close-up cross-sectional view of a pair of alignment structures of the pair of substrates shown in Figure 15B.

[0050] Figure 16A schematically illustrates a perspective view of a pairs of substrates (or wafers) having self-alignment structures comprising cuboidal or rectangular protrusions and holes.

[0051] Figure 16B schematically illustrates a see-through top view of the pairs of substrates shown in Figure 16A when the two substrates overlapped and the self-alignment structures on the first and second substrates are engaged.

[0052] Figure 16C schematically illustrates a side close-up cross-sectional view of a pair of alignment structures of the pair of substrates shown in Figure 16B.

[0053] Figure 17A schematically illustrates a top view of an example integrated optical circuit switch (IOCS) device, similar to the device shown in Figure 2A, having tap couplers and photodiodes for monitoring optical power rerouted to optical ports by the optical switches.

[0054] Figure 17B schematically illustrates a top view of an example IOCS device, similar to the device shown in Figure 2A, having photodiodes for monitoring optical power rerouted to optical ports by the optical switches and optical power passed through the by the switching cells

[0055] Figure 17C schematically illustrates a top view of an example IOCS device, similar to the device shown in Figure 2A, having inline photodiodes for monitoring optical power rerouted to optical ports by the optical switches.

[0056] Figure 18 schematically illustrates a top view of an example IOCS device, similar to the device shown in Figure 2A, having optical switches with integrated capacitive sensors for monitoring optical switch state monitoring.

[0057] Figure 19A schematically illustrates a top view of an example IOCS device having two bus optical waveguides, a primary optical switch, a recovery optical waveguide and recovery optical switches for bypassing the primary optical switch.

[0058] Figure 19B schematically illustrates a top view of an example IOCS device having recovery optical waveguides formed in a single waveguide layer and recovery optical switches for establishing recovery optical paths via the recovery optical waveguides.

[0059] Figure 20A schematically illustrates a top view of an example IOCS device having recovery optical waveguides formed in two waveguide layers and recovery optical switches for establishing recovery optical paths via the recovery optical waveguides.

[0060] Figures 20B-20C schematically illustrate a top view of a first wafer or waveguide layer (20B) and a second wafer or waveguide layer (20C) of the IOCS device shown in Figure 20A.

[0061] Figures 21A-21B schematically illustrate a front view (21A) and a three-dimensional view (21B) an example optical edge coupler for coupling an optical fiber waveguide to an on-chip waveguide.

[0062] Figures 21C-21D schematically illustrate a front view (21C) and a three-dimensional view (21C) of another example optical edge coupler for coupling an optical fiber waveguide to an on-chip waveguide.

[0063] Figures 21E-21F schematically illustrate a front view (21E) and a three-dimensional view (21F) of another example optical edge coupler for coupling an optical fiber waveguide to an on-chip waveguide.

[0064] Figures 22A-22B schematically illustrate a front view (22A) and a three-dimensional view (22B) of an edge coupler interposer configured to optically couple a one-dimensional (1D) array of optical ports along an edge of a photonic chip to a two-dimensional (2D) array of optical ports.

[0065] Figure 22C schematically illustrates a top view of an IOCS device having two sets of optical ports along two different edges of the IOCS device and two edge coupler

interposers each edge coupler interposer aligned and optically coupled to one set of optical ports.

DETAILED DESCRIPTION

[0066] Signal operation in the optical domain can significantly increase the bandwidth and reduce loss in data processing and transport compared to operation in electrical domain. As such it can be advantageous to perform at least a portion of data processing and transport tasks required in an application, in an optical domain. One of the important tasks in any computing or communication operation, is controlling signal paths in a network of signal channels. In many applications, this task is performed by switching circuits comprising a plurality of reconfigurable interconnections among the signal channels. Optical switch networks and circuits are modules that can provide reconfigurable optical interconnection between a plurality of optical channels (e.g., optical waveguides) and can replace their electrical counterpart when data processing and transport is performed in the optical domain. Such optical switching modules may comprise a plurality of optically interconnected switching cells, each configured to control optical signal flow between at least two individual optical channels of the module. Optical switch networks and circuits can have much lower power requirements than electrical switch networks and circuits.

[0067] In some implementations, optical switching cells (also referred to as switching cells) may be used to form a network of controllable optical interconnections between optical waveguides. In some implementations, the optical waveguides may form a matrix structure or arrangement comprising a first array of optical waveguides (e.g., horizontal waveguides) and a second array of optical waveguides (e.g., vertical waveguides) forming a matrix of waveguide crossings. In some implementations, a waveguide crossing may comprise overlapping portions of a waveguide of the first array of optical waveguides and a waveguide of the second array of optical waveguides. In some implementations, transmission of light through a waveguide crossing can be made reconfigurable using an optical switch. The reconfigurable waveguide crossing can controllably couple light propagating in one of the waveguides to the other of the waveguide of the waveguide crossing.

[0068] A switching cell can be a reconfigurable optical waveguide crossing comprising at least one pair of fixed-position bus optical waveguides of an optical network and

an optical switch comprising a movable optical waveguide portion (e.g., a shunt waveguide) that can be optically coupled with and decoupled from each of the bus optical waveguides of the pair of bus optical waveguides by controlled actuation (e.g., electromechanical actuation). In such cases, a first bus optical waveguide of the pair of the bus optical waveguides provides optical connection between first and second optical ports of the optical network and a second bus optical waveguide of the pair of the bus optical waveguides provides optical connection between third and fourth optical ports of the optical network. The bus optical waveguides may cross each other at a crossing region such that, when the optical switch is in its ON state, the shunt waveguide optically connects the first optical port to the third optical port and optically disconnects the first optical port from the second optical port by coupling light from the first bus optical waveguide to the second bus optical waveguide. In some embodiments, the shunt waveguide may comprise a bent (e.g., L-shape) waveguide configured to couple light from a bus waveguide to another bus waveguide via two coupling regions of the shunt waveguide. Each coupling region can be close to an end of the shunt waveguide and can be configured to couple light from a bus waveguide to the shunt waveguide when the optical switch is the ON state (e.g., upon being mechanically actuated).

[0069] Some examples of optical waveguide networks comprising switching cells having optical switches are discussed in U.S. Pat. No. 10,061,085 issued August 28, 2018, which is hereby incorporated by reference herein in its entirety. It will be understood that, to the extent that any of the incorporated content may interpreted to be contradictory to corresponding content of the present disclosure, the present disclosure shall control.

[0070] Some of the existing optical switch networks are implemented based on optical switch and optical waveguide configurations fabricated on a single substrate where the bus optical waveguides are formed on a single waveguide layer. When two bus optical waveguides of an optical switch network are within the same waveguide layer (e.g., they are fabricated by patterning the same layer on a substrate), the two bus optical waveguides will physically cross each other at a waveguide crossing where an optical switch is disposed to controllably reroute light between them. Given that when the optical switch is in the OFF state the two bus optical waveguides should be optically isolated, the waveguide crossing should be designed such that when light propagating in one of the two bus optical waveguides can pass through the waveguide crossing without leaking or getting coupled to the other bus optical

waveguide. Additionally, the waveguide crossing should support low loss transmission via each one of the bus optical waveguides. Designing a waveguide crossing that satisfies these conditions can be a challenging task; as such, optical switch networks having bus optical waveguides in a single waveguide layer may have poor performance due to one or both high insertion loss or high optical cross talk at individual waveguide crossings. Given that an optical switching circuit may include a large number of switching cells, and thereby a large number of waveguide crossings, even a low level of optical insertion loss and optical cross-talk at an individual switching cell may result in a significant loss for a single optical channel of the optical switching network (which passed through multiple switching cells), and leakage of light to all the waveguides crossing that optical channel.

[0071] One solution to the above-mentioned problem can be fabrication of the two bus optical waveguides, which should be controllably connected via an optical switch, on two vertically separated waveguide layers. Using this approach one bus optical waveguide can cross over the other one while the two waveguides remain optically isolated. The optical switching between such bus optical waveguides can be achieved using an optical switch configured to controllably couple the two vertically separated optical waveguides. However, integrating an optical switch, particularly a microelectromechanical systems (MEMS) optical switch, with such dual layer structure is not trivial since the waveguide sections and the MEMS actuator include moving parts that should be released for the optical switch to work.

[0072] This disclosure describes structures, designs, and methods for fabricating integrated optical switches and networks that comprise optical switching cells formed by bus optical waveguides that are vertically separated from each other and are controllably coupled by MEMS optical switches configured to reroute light between the bus optical waveguides.

[0073] The disclosed designs and structures may be used to fabricate optical switches and optical switching cells having lower optical crosstalk (in OFF state), and lower optical insertion loss compared to existing optical switches and optical switching cells. The improved performance of the disclosed optical switches is in part a result of using methods that enable fabricating optical switching cells having vertically separated bus optical waveguides and microelectromechanically activated optical switches. Additionally, the fabrication methods described herein can reduce the cost and complexity of the dual-layer

optical switching circuits and facilitate mass production of reliable and high performance integrated optical circuit switches.

[0074] The disclosed optical switches and switching cells may be fabricated using fabrication technologies used for fabricating complementary metal-oxide-semiconductor (CMOS) device structures. As such, in some embodiments, these optical switches and switching cells can be built directly on a silicon chip by leveraging capabilities of CMOS foundries and, in some implementations, at least partially co-fabricated with CMOS devices, and electronic circuits (e.g., a control circuit that controls the optical switches) on a common chip.

[0075] The disclosed optical switching circuits and the corresponding optical switching cells may be used in a variety of applications including, but not limited to, communication, data centers, high performance computing (HPC), and artificial intelligence (AI) and machine learning (ML) AI/ML systems, and other applications.

[0076] Figure 1 schematically illustrates an example optical switch network (OSN) 100 having a matrix architecture. The OSN 100 comprises a first plurality of bus optical waveguides 102 that are controllably interconnected to a second plurality of bus optical waveguides 104 using a matrix of switching cells (SC1, SC2, ..., and SC12). When all switching cells are in an OFF state, the first plurality of bus optical waveguides 102 optically connect a first plurality of optical ports 106 to a second plurality of optical ports 108, and the second plurality of bus optical waveguides 104 optically connect a third plurality of optical ports 112 to a fourth plurality of optical ports 113.

[0077] In the example shown, for illustrative purposes, the first plurality of bus optical waveguides 102 includes four waveguides, the second plurality of optical waveguides 104 includes three waveguides, and the matrix of switching cells includes twelve switching cells SC1-SC12. In some implementations, each switching cell provides controllable optical coupling between an individual waveguide of the first plurality of bus optical waveguides 102 and an individual waveguide of the second plurality of bus optical waveguides 104. In some embodiments, an individual switching cell can include at least one optical switch configured to optically couple one of the waveguides of the first plurality of bus optical waveguides 102 to one of the waveguides of the second plurality of bus optical waveguides 104. For example, when a switching cell is in the ON state, an optical switching cell of the switching cell may

reroute an optical signal received from one port of the first plurality of optical ports 106 to one port of the third plurality of optical ports 112 or vice versa. In some such embodiments, when the switching cell is in the ON state, the same optical switch may not reroute an optical signal received from one port of the second plurality of optical ports 108, to one port of the third plurality of optical ports 112 or of the fourth plurality of optical ports 113. In some embodiments, an individual switching cell may comprise two optical switches configured to controllably couple one optical waveguide of the first plurality of waveguides 102 to an optical waveguide of the second plurality of waveguides 104. In some such embodiments, when both optical switches of the switching cell are in the ON state an optical signal received from one port of the first plurality of optical ports 106, is rerouted to one port of the third plurality of optical ports 112 or vice versa, an optical signal received from one port of the second plurality of optical ports 108 is rerouted to one port of the third plurality of optical ports 112 (or vice versa) or to one port of the fourth plurality of optical ports 113.

[0078] In some embodiments, an OSN may be implemented based on an integrated photonic circuit (IPC) comprising bus optical waveguides and optical switches fabricated on one or more substrates. In some implementations, the fabrication of the optical switches and/or bus optical waveguides may comprise monolithic fabrication and wafer-scale integration (WSI). In some embodiments, a switching cell may comprise portions of two bus optical waveguides and one or more optical switches configured to controllably couple optical signals from one bus optical waveguide to another. In some implementations, an optical switch may comprise a microelectromechanical systems (MEMS) optical switch.

[0079] As described herein, a MEMS switch, a MEMS optical switch, or a MEMS actuator may comprise a switch, optical switch, or an actuator that can be a micro-electro-mechanical system (MEMS) or may comprise one or more features that are micro-electro-mechanical. For example, a MEMS switch, MEMS optical switch, or a MEMS actuator can include a design, structure, and/or activation mechanism used in microelectromechanical systems (MEMS). As such MEMS-based optical switch or a MEMS-based actuator may be also referred to as MEMS switch, MEMS optical switch, or MEMS actuator. Microelectromechanical systems may comprise microscopic devices incorporating electronic components, moving parts, and actuators configured to electronically activate or move the moving parts.

[0080] In some embodiments, an individual switching cell (SC1, SC2, ..., or SC12) of the OSN 100 may comprise an optical switch positioned near a crossing region where a first bus optical waveguide of the first plurality of bus optical waveguides 102 crosses over or under a second bus optical waveguide of the second plurality of bus optical waveguides 104 and sections of the first and second bus optical waveguides associated with the crossing region. The optical switch may be configured to optically couple the first and second optical bus waveguides in an ON state and allow substantially uninterrupted transmission of light via the first and second bus optical waveguides in an OFF state. For example, when the optical switch of a SC is in the OFF state, light provided to a respective optical port of the first plurality of optical ports 106 may be transmitted to a respective optical port of the second plurality of optical ports 108 through the SC. When the optical switch of a SC is in the ON state, however, light provided to the optical port may be transmitted to a respective optical port of the third plurality of optical ports 112 by the optical switch. In some implementations, the SC may include a shunt waveguide and an actuator (e.g., a microelectromechanical actuator) configured to controllably couple the shunt waveguide to two bus optical waveguides associated with the SC.

[0081] This disclosure provides OSNs comprising integrated optical circuit switching (IOCS) device based on microelectromechanical systems (MEMS) technology. Some embodiments and methods disclosed here provide IOCS devices comprising a first wafer (or substrate) bonded to a second wafer (or substrate). For example, the OSN 100 may comprise such IOCS device formed by bonding two wafers (or substrates). In some implementations, at least one of the first and second wafers may comprise an integrated photonic circuit (IPC). In some implementations, at least one of the first and second wafers may comprise micro-fabricated structures. In some embodiments the first wafer may comprise the first plurality of bus optical waveguides 102 and the optical switches of the switching cells (SC1, SC2, ..., and SC12), and the first wafer may comprise the second plurality of bus optical waveguides 104. In some implementations, an IOCS device may be fabricated by aligning and bonding (e.g., flip-chip bonding) of the first and second wafers to form the network of SCs that can controllably couple the individual bus optical waveguides of the first plurality of bus optical waveguides 102 to those of the second plurality of bus optical waveguides 104. In some embodiments, before bonding, the actuators and shunt waveguides of the first wafer can be

substantially completely fabricated and even be fully functional. For example, the shunt waveguides and/or actuators may be released to allow their mechanical movements. In some other embodiments, a fabrication step of the actuators and/or shunt waveguides (e.g., releasing the corresponding MEMS actuator and/or suspending the shunt waveguide) may be performed after bonding the first wafer to the second wafer. In some such embodiments, after bonding the first and second wafers and before completing the fabrication of the optical switches and/or shunt waveguides, a substrate or a layer of the second wafer may be removed (e.g., detached) from a waveguide layer comprising the second plurality of bus optical waveguides 104.

Integrated Optical Switching Networks

[0082] Figure 2A shows a top view schematic of an example an example IOCS device 200 having a first and third pluralities of optical ports 106, 112, and first and second pluralities of bus optical waveguides 102, 104. In some implementations, the first and second pluralities of waveguides 102, 104, are vertically separated and are optically isolated. In some embodiments, the first plurality of waveguides 102 may be disposed on a first wafer and the second plurality of waveguides 104 may be disposed on a layer (e.g., a substrate, a wafer, or a buffer layer) vertically separated from and/or at least partially suspended above the wafer. In some implementations, the first plurality of waveguides 102 extend in a first direction and the second plurality of waveguides 104 extend in a second direction different from or crossing the first direction. As such an individual waveguide of the first (or second) plurality of waveguides passes through multiple crossing regions associated with the individual waveguide crossing over or below an individual waveguide of the second (or first) plurality of waveguides. In the absence of an optical switch two waveguides passing through a crossing region are optically isolated. In some implementations, an optical switch 207 may be disposed at or near a crossing region to form an optical switching cell (SC) 208. The optical switch 207 may be configured to optically couple the waveguides passing through the crossing region (or the optical switching cell) when it is actuated. In some embodiments, the optical switch 207 may comprise a shunt optical waveguide (also referred to as shunt waveguide) located at or near the crossing region, and sections of bus optical waveguides associated with the crossing region. The shunt waveguide may comprise a short waveguide section extending from a first end to a second end both located in the SC 208. The optical switch 207 may further include an actuator (e.g., a

microelectromechanical system actuator or MEMS actuator) configured to, when actuated, move an end region of the shunt waveguide toward the first or the second waveguide, to optically couple that end region to the first or second waveguides. In some embodiments, the optical switch 207 can include two actuators (e.g., a microelectromechanical systems actuator or MEMS actuator) configured to move the first and second end regions of the shunt waveguide toward the first and the second waveguides respectively (when actuated) to optically couple the first and second waveguides. In some implementations, the MEMS actuator, the shunt waveguide, and the first waveguide may be fabricated on a common wafer or substrate.

[0083] In some implementations, the optical ports labeled “A1”, “A2”, ..., “Am”, are connected to and are in optical communication with the bus optical waveguides of the first plurality of bus optical waveguides 102 and the optical ports labeled “B1”, “B2”, ..., “Bm”, are connected to and are in optical communication with the bus optical waveguides of the second plurality of bus optical waveguides 104. In some implementations, an individual optical port of the first or third plurality of optical ports 106, 112 can be connected to a first end of the corresponding bus optical waveguide (also referred to as bus waveguide) and may be used bi-directionally as optical input (e.g., for receiving light from an optical fiber, a device, an optical waveguide on another PIC) and optical output (e.g., for transmitting light to an optical fiber, a device, an optical waveguide on another PIC). In some implementations, a second end of the individual waveguide can be in optical communication with another optical device or waveguide (e.g., an optical waveguide external to the IOCS device 200) and may be configured to transmit light to and/or receive light from the optical device or waveguide. In some implementations, the other optical device or waveguide may be fabricated on the same chip, wafer, or substrate, on which the first plurality of waveguides 102 or the second plurality of waveguides 104 are fabricated. In some implementations, the other optical device or waveguide may be fabricated on a separate chip, wafer, or substrate, mounted on a carrier chip on which a wafer, chip, or substrate that includes the first plurality of waveguides 102 or the second plurality of waveguides 104 is mounted.

[0084] In some embodiments, an IOCS device may comprise a first plurality of waveguides 102 extending from a first plurality of optical ports 106 to a second plurality of optical ports 108, and a second plurality of waveguides 104 extending from a third plurality of optical ports 112 to a fourth plurality of optical ports 113. An example such embodiments is

the IOCS device 201 shown in in Figure 2B. The IOCS device 201 comprises four sets of input/output optical ports, labeled “A1”, “A2”, ..., “Am”, “B1”, “B2”, ..., “Bn”, “C1”, “C2”, ..., “Cm”, and “D1”, “D2”, ..., “Dn”. In some implementations, these optical ports may be referred to as “input”, “output”, “drop”, “through”, and “add” ports, respectively. In various implementations, an individual optical port of any of these four sets may be used to receive and transmit light.

[0085] In some embodiments, an optical port of an IOCS device may comprise a surface optical coupler (e.g. a grating coupler) configured to couple a beam of light incident on the optical port in a direction perpendicular to a major surface of the substrate on which a waveguide is fabricated, to a waveguide of the IOCS device. For example, a surface optical coupler may couple light from an optical fiber vertically positioned above the surface optical coupler to a waveguide of the IOCS device. As another example, a surface optical coupler may couple light from another surface optical coupler, vertically positioned above the surface optical coupler, to a waveguide of the IOCS device. Figure 2C schematically illustrates an example IOCS device 202 having optical ports 206 comprising surface optical couplers. In some implementations, the IOCS device 202 may comprise one or more features described above with respect to the IOCS device 200. In the example shown, the first and second pluralities of optical ports 106, 108, which provide optical connection to the first and second pluralities of waveguides 104, comprise surface optical couplers 205. In some implementations, two adjacent (e.g., immediately adjacent) surface optical couplers may be located at different longitudinal positions with respect to an edge of the IOCS device 202 such that they can receive light from two adjacent waveguides (e.g., two optical fibers). Advantageously, such configuration of optical surface couplers (shown in Figure 2C), can provide more space between the two optical surface couplers for placement of optical fibers and prevents optical cross talks between the surface optical couplers when light is received from two other surface optical couplers vertically positioned above the respective optical surface couplers (e.g., on a second substrate).

[0086] In some embodiments, IOCS devices 200, 201, and 202 may comprise a plurality of optical switches at a plurality of crossing regions formed between the first and second pluralities of waveguides 102, 104 to controllably couple individual waveguides of the first plurality of waveguides 102 to the individual waveguides of the second plurality of

waveguides 104. In some embodiments, the plurality of the optical switches can be configured to controllably couple an optical port at a first edge of an IOCS device to an optical port at a second of the IOCS device. For example, when optical switch 210 of IOCS devices 200, 201, and 202 in an ON state (actuated) and all optical switches between optical port A1 and the optical switch 210 are in an OFF state, the optical switch 210 couples the optical port A1 to optical port B3 and reroutes light received by optical port A1 to optical port B3 and vice versa. When all optical switches associated with waveguide that is optically connected to optical port A1 are in an OFF state, the optical port A1 is decoupled from optical ports B3-Bm and light received by optical port A1 is transmitted through the corresponding crossing regions.

[0087] In some embodiments, the plurality of the optical switches can be configured to controllably couple an optical port at a first edge of an IOCS device to an optical port at a second edge of the IOCS device or to an optical port at a third edge of the IOCS device. An example of such IOCS device is shown in Figure 2D. In this example, the optical switches 211a and 211b are configured to controllably couple optical port A1 (at a first edge of the IOCS device 203) to the optical port B3 (at a second edge of the IOCS device 203), and/or optical port B4 (at a third edge of the IOCS device 203). For example, when the optical switch 211a is in an ON state and all optical switches between optical port A1, and the optical switch 211a are in an OFF state, the optical switch 211a reroutes light received from the optical port A1 to the optical port B3. As another example, when the optical switch 211b is in ON state and all optical switches between port A1 and the optical switch 211b are in OFF state, the optical switch 211b reroutes light received by the optical port A1 to the optical port B4.

[0088] In some embodiments, a switching cell (SC) may comprise one waveguide crossing and two optical switches configured to controllably couple a first waveguide associated with the SC to a second waveguide. In some such embodiments, a first optical switch may be configured to controllably couple a first optical port connected to the first waveguide to a second optical port connected to the second waveguide and a second optical switch may be configured to controllably couple the first optical port to a third optical port connected to the second waveguide. In some implementations, the first, second, and third optical ports may be positioned at three different edges of the IOCS device.

[0089] In various embodiments, an individual optical port of the first, second, third, or fourth plurality of optical ports, 106, 108, 112, or 113, may be used bi-directionally as

optical input (e.g., for receiving light from an optical fiber, a device, an optical waveguide on another PIC) and optical output (e.g., for transmitting light to an optical fiber, a device, an optical waveguide on another PIC).

[0090] In some implementations, by selectively turning on some of the optical switches, a one-to-one optical connection map between the first and second pluralities of optical ports 106 and 112 (e.g., ports “A” and “B”) can be established, and the connection configuration can be changed as desired by controlling the states of the optical switches.

[0091] In some embodiments, an optical switch that controllably couples a first waveguide to a second waveguide may be configured such that, when the optical switch is actuated (is in ON state), an amount of optical power that passes through the corresponding crossing region via the first waveguide is less than 1%, less than 3%, less than 5%, or less than 10%. In some implementations, where the first waveguide is optically coupled to a first optical port and the second waveguide is optically coupled to a second optical port, when the optical switch is actuated, more than 90%, more than 95%, more than 97%, or more than 99% of the optical power received from the first optical port may be rerouted to the second optical port by the optical switch (e.g., via a shunt waveguide of the optical switch optically coupled to the first and second waveguides).

[0092] In some implementations, a bus waveguide of the first or second plurality of bus waveguides can be extended from a first end optically connected to and in optical communication with an optical port to a second end optically connected to an optical element. In some implementations, the optical element may be fabricated on the waveguide layer, substrate, or wafer on which the bus waveguide is fabricated. For example, the IOCS device 200 (Figure 2A) can be a portion of an IPC fabricated on a wafer and the waveguides 102 and or 104 can be optically connected to one or more photonic components (e.g., photodetectors, modulators, filters, directional couplers wavelength multiplexers, and the like).

[0093] In some embodiments, a port on a substrate, chip, or wafer may comprise an optical coupler configured to couple light from an external optical waveguide (e.g., an optical waveguide that is not fabricated on the same substrate, chip, or wafer). In some implementations, a port on a substrate may comprise a fiber-optic coupler configured to optically connect a bus waveguide fabricated on the same substrate as an optical fiber waveguide. In some implementations, an optical port on a substrate may comprise a vertical

optical coupler configured to optically connect a bus waveguide fabricated on the same substrate to a bus waveguide on another substrate. For example, the optical ports B1,..., Bm may comprise vertical optical couplers fabricated on wafer 1 and can be optically connected to the waveguides 104 on wafer 2.

[0094] In some implementations, an IOCS device may comprise a single die and the corresponding bus waveguides may be optically connected to external optical waveguides (e.g., optical fibers) via a plurality of optical ports.

[0095] In some implementations, an IOCS device (e.g., the IOCS device 200, 201, 202, or 203) may comprise two bonded integrated circuits or may be formed by bonding two integrated circuits. In various embodiments, an integrated circuit may comprise a photonic integrated circuit (PIC), and/or a microstructure substrate. In some implementations, an integrated circuit may comprise an optical waveguide, an optical switch, a MEMS actuator, a microelectromechanical structure, microstructure features for active or passive alignment of the integrated circuit with another integrated circuit or wafer. In some implementations, an integrated circuit may be formed on a substrate, a wafer, a die or the like.

[0096] In some embodiments, a portion of the elements of the IOCS device may be fabricated on a first substrate and while remaining elements are fabricated on a second substrate before the two substrates are bonded to form the IOCS device. In some implementations, bonding the two substrates may comprise aligning the two substrates (passively and/or actively) and flip-chip bonding them together. In some implementations, bonding may comprise wafer scale bonding. For example, two wafer each comprising microstructure features may be bonded to form a bonded wafer comprising a plurality of IOCS devices. In some implementations, a portion of the fabrication steps (e.g., releasing the MEMS actuators) may be performed after bonding the two wafers. In some implementations, the bonded wafer may be divided into a plurality of individual IOCS devices using a dicing tool.

[0097] In some implementations, the first plurality of bus optical waveguides or waveguides 102 (associated to ports “A”) may be formed on a first substrate or wafer “wafer 1”, and the second plurality of bus optical waveguides or waveguides 104 (associated with ports “B”) may be formed on a second substrate or wafer “wafer 2”. In some implementations, the first plurality of waveguides 102 of wafer 1 can be substantially located in a first waveguide layer of wafer 1 extending parallel to a major surface of the wafer 1, and the second plurality

of waveguides 104 of wafer 2 can be substantially located in a second waveguide layer of wafer 2 extending parallel to a major surface of the wafer 2. In some embodiments, wafer 2 may be located above wafer 1 and bonded to wafer 1 such that the first and second waveguide layers are substantially parallel to each other and the two sets of waveguides 102, 104 form a plurality of crossing regions where a crossing region comprises a region (e.g., on wafer 1) where a projection (e.g., a vertical projection) of a waveguide in the second waveguide layer overlaps with a waveguide in the first waveguide layer. It should be understood that the waveguides of wafer 1 are optically isolated and do not physically cross the waveguides of wafer 2, however they may appear to cross within a crossing region in the top view. For example, the top view of the IOCS device 201 shown in Figure 2B can be a top view of wafer 1, which includes the first plurality of bus waveguides 102, aligned and overlapped with wafer 2, which includes the second plurality of bus waveguides 104. In some implementations, wafer 1 may comprise a first plurality of spacer portions and the wafer 2 may comprise a second plurality of spacer portions, where upon bonding wafer 1 and wafer 2, spacer portions of wafer 1 and the respective spacer portions of the wafer 2 form spacer structures configured to define a vertical separation between the first and second waveguide layers. In some implementations, spacer or mechanical stopper portion may be vertically extended away from the corresponding wafer. In various embodiments, a spacer (or mechanical stopper) portion may have any cross-sectional shape including and not limited to circular, rectangular, oval, square, triangular, or the like. a first spacer portion formed on wafer 1 and a second spacer portion formed on the wafer 2 may be contacted or bonded to form a spacer structure that defines a vertical separation between the first and second waveguide layers.

[0098] In some implementations, wafer 1 may comprise a first plurality of bonding pads or regions, wafer 2 may comprise a second plurality of bonding pads or regions. In such implementations bonding of wafer 1 to wafer 2 may comprise bonding the first and second pluralities of the bonding pads or regions. In some implementations, the first and second pluralities of the bonding pads may comprise the first and second pluralities of the spacer portions. As such, In some implementations, the first plurality of spacers (or mechanical stoppers) may be bonded to the second plurality of wafers to provide bonding between wafers 1 and 2 and establish a vertical separation between wafer 1 and wafer 2. The spacers as disclosed herein may be used, e.g., in integration schemes where at least portions of an optical

switch and/or an actuator are released prior to bonding the wafers (“pre-bonding MEMS release process”). In this integration scheme, because the spacers may be the primary mechanical structures that come into contact and bonded to each other, the spacers should have such substantial cross-sectional area or width to provide sufficient mechanical support during and after the bonding process. In some implementations, a cross-sectional area of a spacer or mechanical stopper portion can be larger than 10, larger than 100, larger than 300, larger than 500, or larger than 700, larger than 1000 square microns, or within any ranges formed by these values or larger or smaller values. While in this paragraph, the spacers are described as being present on both wafers 1 and 2, embodiments are not so limited. In some embodiments, spacers may be provided on one but not the other of wafers 1 and 2. It will be appreciated that, in addition to the width or the cross-sectional area, the heights of the first and second spacers may be critically controlled, such that the optical switch can effectively switch by mechanical coupling between the waveguides in the wafers 1 and 2.

[0099] In some implementations, the first plurality of waveguides 102 of wafer 1 can be substantially located in a first waveguide layer of wafer 1 parallel to a major surface of the wafer 1, and the second plurality of waveguides 104 can be substantially located in a second waveguide layer parallel to a major surface of the wafer 2, where the second waveguide layer is clamped to the wafer 1 via a plurality of anchors formed on wafer 1 such that the first and second pluralities of waveguides 102, 104 form a matrix of crossing regions as described above. In some embodiments, the second waveguide layer may include a support layer and the second plurality of waveguides 104 formed on the support layer but may not include a substrate. The support layer may be substantially thinner than a substrate. For example, the support layer may include a buried oxide left after removing a bulk portion of a silicon-on-insulator (SOI) wafer. In some implementations, an anchor of the plurality of anchors may be formed on wafer 1 and vertically extend away from wafer 1. The anchors as disclosed herein may be used, e.g., in integration schemes where portions of an optical switch and/or an actuator are released after bonding the wafers (“post-bonding MEMS release process”). In this integration scheme, the sacrificial material supporting the optical switch and/or the actuator spacers may provide the mechanical support as well as additional bonding interfaces. In some implementations, the anchors may have smaller cross-sectional area or width relative to those of the spacers describe above, in the context of the pre-bonding MEMS release process. In

various embodiments, the anchor may have any cross-sectional shape including and not limited to circular, rectangular, oval, square, triangular, or the like. In some implementations of an anchor can be less than 100 square microns, less than 10 square microns, or less than 1.0 square microns. While in this paragraph, the anchors are described as being present on wafer 1, embodiments are not so limited. In some embodiments, anchors may be provided on both wafers 1 and 2, in an analogous manner as that described above with respect to the pre-bonding MEMS release process. It will be appreciated that, in addition to the width or the cross-sectional area, the height of the anchor may be critically controlled, such that the optical switch can effectively switch by mechanical coupling between the waveguides in the wafers 1 and 2.

[0100] According to various embodiments described herein, wafers 1 and 2 may be direct-bonded to each other. In direct bonding, chemical bonds are formed directly between suitable surfaces without using an adhesive. Advantageously, low temperature direct-bonding may be used for realizing flexibility of the integrated materials. When low temperature direct-bonding is employed, bonding may be performed at temperatures less than about 400oC, 300oC, 200oC and 100oC or even room temperature, or a temperature in a range defined by any of these temperatures. Suitable surfaces formed by the spacers or anchors include Si, SiO₂ and metals. According to some embodiments described herein, wafers 1 and 2 may be hybrid-direct bonded to each other. However, embodiments are not so limited and in other embodiments, adhesives may be used.

[0101] In some embodiments, the shunt waveguides of the optical switches of an IOCS device (e.g., the IOCS device 200, 201, 202, or 203) may be formed in a middle waveguide layer above the first waveguide layer and below the second waveguide layer. As manufactured, the middle waveguide layer may be vertically separated from the first and second waveguide layers. In some implementations, a vertical separation between the middle waveguide layer and the first and/or second waveguide layers can be from 0.1 microns to 0.5 microns, 0.5 microns to 1 micron, from 1 micron to 2 microns, from 2 microns to 5 microns, from 5 microns to 7 microns, or larger values. In some embodiments, the middle waveguide layer may be suspended above the first waveguide layer and supported by clamping structures connected to the first waveguide layer or a substrate on which the first waveguide layer is formed. In some implementations, the middle waveguide layer may comprise the shunt waveguides and supporting structures configured to support the shunt waveguide. In some

implementations, the supporting structures may comprise flexible support structures configured to movably support end regions of each shunt waveguide such that they can vertically move toward the first or second waveguide layers.

[0102] In some implementations, the bus optical waveguides and shunt optical waveguides of an IOCS device may comprise polycrystalline silicon, single crystal silicon (also referred to as monocrystalline silicon), silicon nitride, or other materials. In some embodiments, the bus optical waveguides and shunt optical waveguides of an IOCS device may have a propagation loss less than 1 dB/cm, less than 0.5 dB/cm, less than 0.1 dB/cm, less than 0.01 dB/cm, or smaller values for light having a wavelength within an operational wavelength range of the IOCS and the switching cell therein. In some implementations, the operational wavelength range of the IOCS or a switching cell therein, can be from 400 nm to 1100 nm to 1200 nm, from 1200 nm to 1400 nm, 1400 nm to 1500 nm, from 1500 nm to 1600 nm, from 1260 to 1360 nm, from 1450 to 1650nm or any ranges within ranges formed by these values or larger or smaller values.

Optical Switching Cell (SC)

[0103] Figure 3A schematically illustrates a top view and two side cross-sectional side views of an example switching cell (SC) 208 in an OFF state. The switching cell 208 can be the switching cell 208 in the IOCS device 200, 201, 202, or 203, as shown in Figures 2A, 2B, 2C and 2D). The SC 208 may comprise portions of a first waveguide 302 of the first plurality of the waveguides 102 and a second waveguide 304 of the second plurality of waveguides 104 near a crossing region of the first and second waveguide 302, 304. The first waveguide 302 is vertically separated from the second waveguide 304. The SC 208 may further comprise an optical switch configured to controllably couple the first waveguide 302 to the second waveguide 304. When the optical switch is in the OFF state, the first and second waveguides 302, 304 are optically decoupled from each other. The optical switch may comprise a shunt waveguide 306, and one or more MEMS actuators. The shunt waveguide 306 is vertically (and optically) separated from the first and second waveguides 302, 304 and extends lengthwise from a first end above the first waveguide 302 to a second end below the second waveguide 304. In some examples, the shunt waveguide 306 may be connected or anchored to a substrate by a switch anchor configured to suspend the shunt waveguide such

the end regions of the shunt waveguide can move with respect to the substrate and the first and second waveguides 302, 304. In the OFF state, for sufficient optical decoupling, a vertical separation between the shunt waveguide and the first and/or second waveguides 302, 304 can be from 0.1 microns to 0.5 microns, from 0.5 microns to 1 micron, from 1 micron to 2 microns, from 2 microns to 3 microns, from 3 microns to 4 microns, or a value in a range defined by any of these values, or larger values. In some implementations, a middle portion of the shunt waveguide between a first end region 306a and a second end region 306b may be held in place or fixed by clamping support structure connected to the first waveguide layer or a substrate on which the first waveguide 302 is formed. In the OFF state, one or both of the first end region 306a, near the first end of the shunt waveguide 306, and the second end region 306b, near the second end of the shunt waveguide 306 may be vertically (and optically) separated from a respective one of the first waveguide 302 and the second waveguide 304. In some implementations, the first end region 306a (also referred to as first coupling region) may be positioned above the first waveguide 302 such that when an actuator moves the first end region 306a toward the first waveguide 302, the first end region 306a becomes optically coupled to the first waveguide 302. Similarly, the second end region 306b (also referred to as second coupling region) may be positioned below the second waveguide 304 such that when an actuator moves the end region 306b toward the second waveguide 304, the second end region 306b becomes optically coupled to the second waveguide 304. In some embodiments, a first MEMS actuator may control a vertical position of the first end region 306a with respect to the first waveguide 302 and a second MEMS actuator may control a vertical position of the second end region 306b with respect to the second waveguide 304. In some embodiments, the 1st and 2nd MEMS actuators may comprise electrostatic actuators. In some other embodiments, the first MEMS actuator may comprise a capacitive electrostatic actuator and the second MEMS actuator may comprise one or more seesaw actuators. In various other implementations, the first and second MEMS actuators may include, without limitation, electrothermal, thermal, magnetic, electromagnetic, electrostatic combdrive, magnetostrictive, piezoelectric, fluidic, pneumatic actuators, and the like. In various embodiments, a MEMS actuator may comprise a piezoelectric actuator comprising a piezoelectric material configured to operate in different a longitudinal, transversal, shear or other modes. The piezoelectric material may comprise an inorganic or an organic piezoelectric material. The inorganic piezo electric material may

comprise a single crystal or a ceramic (e.g., lithium niobate, quartz, aluminum nitride, PMN-pT, PZN-PT, or the like), or a polymer (e.g., PVDF, polyimide, or the like); however the embodiments are not so limited and other materials may be used.

[0104] Figure 3B schematically illustrates a closeup view of the second end region 306b of the shunt waveguide 306 and the second MEMS actuator comprising a first 310a and a second 310b pairs of seesaw actuators. Figure 3C schematically illustrates a closeup view of the first end region 306a of the shunt waveguide 306 and a flexible support structure that movably supports the first end region 306a. In some implementations, the end regions 306a and/or 306b of the shunt waveguide 306 may comprise a tapered region having a width that is tapered toward an end of the shunt waveguide 306. In some implementations, when a coupling region having a tapered region is actuated and bends toward the respective bus waveguide, an adiabatic optical coupler may be formed by the end region the and the bus waveguide, thereby allowing low loss adiabatic transfer of optical power from the bus waveguide to the shunt waveguide 306 and vice versa. As such tapering the end regions of the shunt waveguide may reduce optical insertion loss for optical coupling from the shunt waveguide 306 to the first and second waveguides and vice versa. In some implementations, the SC 208 may comprise two or more conductive lines or electrodes electrically connected to the first and second MEMS actuators and configured to electrically connect the MEMS actuators to an electronic circuit that controls the state of the optical switch by proving or not providing actuation signals to the MEMS actuators.

[0105] In some implementations, activating the optical switch to an ON state comprises actuating the first actuator (e.g., a MEMS actuator) to move the first end region 306a toward the first waveguide 302 and the second actuator to move the second end region 306b toward the second waveguide 304. When the SC 208, and therefore the optical switch, is in the OFF state, the vertical spacing between shunt waveguide 306 and the first and second waveguides 302, 304 can be large enough to prevent optical coupling between them. In some implementations, when the optical switch is in the OFF state, a portion of light coupled from the first waveguide 302 to the second waveguide 304 (or vice versa) may exist but not exceed 3%, 2%, 1%, 0.1%, 0.01%, or smaller values. When the SC 208, and therefore the optical switch, is in the ON state, the first and second end regions 306a, 306b move toward the first and second waveguides 302, 304, respectively, (e.g., first end region 306a moved up, and the

second end region moves down), such that the first and second end regions 306a, 306b become optically coupled to the first and second waveguides 302, 304, respectively. As such, when the optical switch is in the ON state, light propagating in one of the first or second waveguides 302, 304 is coupled into the other one of the first and second waveguide 302, 304 via the shunt waveguides 306.

[0106] Figure 4 schematically illustrates top view and two side cross-sectional side views of an example switching cell (SC) 208 when the optical switch and therefore the SC 208 is in the ON state. As described above and shown in Figure 4, the first and second end regions 306a, 306b of the shunt waveguide 306 are moved close to the first and second waveguides 302, 304, respectively. In some implementations, the first and second end regions 306a, 306b may not be in contact with the first and second waveguides 302, 304, respectively. In some implementations, when the SC 208 is in the ON state, a gap size (d) between the first end region 306a (or second end region 306b) and the first waveguide 302 (or second waveguide end region 304) can be from $\lambda/100$ to $\lambda/10$, from $\lambda/10$ to $\lambda/8$, from $\lambda/8$ to $\lambda/6$, from $\lambda/6$ to $\lambda/4$, from $\lambda/4$ to $\lambda/2$, where λ is the wavelength of light rerouted by the SC 208. In some implementations, when the optical switch is in ON state the vertical distances between the first and second end regions 306a, 306b, and the first and second waveguides 302, 304 can be small enough to cause more than 90%, more than 93%, more than 95%, or more than 97% of light propagating within one of the first or second waveguides 302, 306 toward an end region of the shunt waveguide 306 to be transmitted to the other one of the first and second waveguides 302, 306 via the shunt waveguide 306. In some implementations, the first and second end regions 306a, 306b may be in contact with the first and second waveguides 302, 304, respectively.

[0107] In some implementations, when the optical switch is in ON state, a specified portion of light propagating within one of the first or second waveguides 302, 304 toward an end region of the shunt waveguide 306 is transmitted to the other first and second waveguides 302, 304 via the shunt waveguide 306. In some implementations, the specified portion can be from 1% to 5%, from 5% to 10%, from 10% to 30%, from 30% to 50%, 50% to 70%, from 50% to 70%, from 70% to 90%, from 90% to 95%, from 95% to 99%, or a value in a range defined by any of these values or larger values.

[0108] In some implementations, the first and second MEMS actuators and/or the actuation signals provided to the first and second MEMS actuators may be configured to control a strength of optical coupling between the first and second end regions 306a, 306b of the shunt waveguide 306 and the respective waveguides.

[0109] In some implementations, in the ON state a vertical distance between the first and second end regions 306a, 306b, and the first and second waveguides 302, 304, respectively, can be from 0.5 micron to 0.3 micron, from 0.3 micron to 0.2 micron, from 0.2 micron to 0.1 micron, from 0.1 micron to 0.01 micron, or a value in a range defined by any of these values or smaller values. In some implementations, in the OFF state a vertical distance between the first and second end regions 306a, 306b, and the first and second waveguides 302, 304, respectively can be from 0.1 microns to 1 micron, 1 micron to 2 microns, 2 microns to 3 microns, 3 microns to 4 microns, or a value in a range defined by any of these values or larger values.

[0110] In various embodiments, switching cell 208 may be fabricated on a silicon substrate using semiconductor fabrication methods and processes.

[0111] Figure 5A schematically illustrates a vertical cross-sectional side view of the SC 208 along a curved cut surface A'A showing the corresponding portions of the first and second waveguides 302, 304, the shunt waveguide 306, and the MEMS actuators that control the end regions 306a, 306b, of the shunt waveguide 306. In some examples, the shunt waveguide 306 may be suspended by a switch anchor 508 extending from a middle region of the shunt waveguide 306, between two end regions 306a, 306b, of the shunt waveguide 306, and a substrate (not shown) on which the first waveguide 302 is formed. The switch anchor 508 may be configured to allow the end regions 306a, 306b to move with respect to the substrate and the first and second waveguides 302, 304.

[0112] In the illustrated example of the first MEMS actuator, which controls the first end region 306a, is a capacitive actuator comprising a first actuating electrode disposed on the middle waveguide layer, that includes the shunt waveguide 306, and a second actuating electrode disposed on the first waveguide layer or the substrate on which the first waveguide layer is fabricated. In this specific example, the first MEMS actuator may comprise the two actuating electrodes and, in some implementations, the flexible support structure 308 (shown in Figure 3C). In some embodiments, the first MEMS actuator may be activated by generating

an electric potential difference between the first and second actuating electrodes and thereby exerting an electrostatic force on the first end region 306a of the shunt waveguide 306 to move the first end region 306a toward the first waveguide 302. When the electric potential difference between the first and second actuating electrodes is removed, the flexible support structure 308 moves the first end region 306a away from the first waveguide 302 back to its neutral position. In some implementations, the coupling gap and thereby optical coupling strength between the first end region 306a and the first waveguide 302 may be tuned or adjusted by tuning or adjusting electric potential difference between the first and second actuating electrodes of the first MEMS actuator.

[0113] In the example shown in Figure 5A, the second MEMS actuator, which controls the second end region 306b, comprises two pairs of seesaw actuators. Figure 5B schematically illustrates a top closeup view of the optical switch near the second end region 306b showing a tapered end of the shunt waveguide 306 mechanically coupled to the two pairs of seesaw actuators. In some implementations, each seesaw actuator comprises a lever beam 504 rotatably connected to the substrate or the waveguide layer via a torsion joint 506, and an electrostatic actuator (e.g., a capacitive actuator comprising two electrodes) configured to rotate the lever beam 504 around a pivot 507 connected to the torsion joints 506. In some implementations, first end 501 of the lever beam 504 comprise an electrode 503 and a second end of the lever beam 504 can be mechanically coupled to the second end region 306b of the shunt waveguide 306. In some implementations, the second MEMS actuator may be activated by providing an electric potential difference the electrode 503 and an electrode disposed on the first waveguide layer or the substrate causing the first end 501 of the lever beam 504 to move down toward the first waveguide layer or the substrate and thereby cause the second end of the lever beam 504 to go up and push the second end region 306b of the shunt waveguide 306 toward the second waveguide 304. In some implementations, when actuated, the electrodes 503 are electrostatically attracted to the electrodes disposed on the first waveguide layer and substantively in a vertical direction normal to a major surface of the first waveguide layer and cause the respective lever beams 504 to rotate around respective torsion joints 506. When the electric potential difference between the electrodes 503 and the respective electrodes in the first waveguide layer is removed, the second region 306b moves away from the second waveguide 304 back to its neutral position and the first ends of the lever beams 504 go back to

their original positions. In some implementations, the coupling gap and thereby optical coupling strength between the second end region 306b and the second waveguide 304 may be tuned or adjusted by tuning or adjusting electric potential difference between the electrodes 503 and the respective electrode on the first waveguide layer.

[0114] As configured, when the optical switch is in the OFF state, none of the MEMS actuators is actuated and the shunt waveguide 306 is in a neutral position having sufficient vertical separation from the first and second waveguides 302, 304, and light propagating in these waveguides is not affected by the shunt waveguide 306. When the optical switch is in the ON state, both first and second MEMS actuators (e.g., the two pairs of the seesaw actuators) are actuated to move the first end region 306a down and the second end region 306b up, so that light propagating in one of the first and second waveguides 302, 304 is optically coupled into the shunt waveguide 306 and then optically coupled into the other one of the first and second waveguides 302, 304.

Integrated Optical Circuit Switches

[0115] As described above, the integrated optical circuit switch (IOCS) device configurations (e.g., IOCS devices 200, 201, 202, 203) may be implemented in different process integration schemes or architectures.

[0116] It will be appreciated that some process integration schemes or architectures of an IOCS device may share certain common features and characteristics described below with respect to an example IOCS device.

[0117] In some embodiments, an IOCS device may comprise a first substrate (e.g., first wafer or chip), a first waveguide layer formed on the first substrate, a middle waveguide layer suspended above the first waveguide layer and mechanically connected to the first substrate via a first plurality of anchors, and a second waveguide layer suspended above the middle waveguide layer. Referring back to Figures 2A-2D, the first waveguide layer can comprise the first plurality of waveguides 102, the second waveguide layer can comprise a second plurality of waveguides 104, and the middle waveguide layer can comprise a plurality of shunt waveguides configured to optically couple the individual ones of the first and second pluralities of waveguides 102, 104, at the respective crossing regions. The first substrate may also comprise MEMS actuators configured to control the shunt waveguides. In some

implementations, a portion of each MEMS actuator (e.g., one or more electrodes) may be included in the middle waveguide layer. For example, a MEMS actuator (e.g., one of the MEMS actuators of the SC 208) may comprise a first electrode formed on the first substrate and a second electrode formed on the second waveguide layer within a region above the first electrode. In some embodiments, the first and second waveguide layers may comprise a buffer layer on which the first or the second plurality of waveguides are formed. In some implementations, the waveguides may comprise silicon or silicon nitride and the buffer layer may comprise silicon dioxide or another material having a lower refractive index compared to silicon or silicon nitride. In some implementations, the waveguides and the buffer layer may comprise other materials provided that the buffer layer has a lower refractive index compared to the waveguides.

[0118] In various embodiments, a substrate may comprise a bulk layer having a thickness from 100 microns to 2000 microns or larger values. In some implementations, a substrate may comprise a top buffer layer having a lower refractive index than the bulk portion of the substrate. For example, a substrate may comprise bulk portion comprising silicon and a top layer comprising silicon dioxide. In some implementations, a plurality of waveguides may be formed in the buffer layer using photolithography and etching (herein referred to as lithographically patterning). For example, a silicon waveguide may be formed on a silicon dioxide buffer layer. In some implementations, substrate may comprise the bulk substrate without any buffer layer.

[0119] In various embodiments, a waveguide layer may comprise a layer formed on a substrate. In some implementations, a waveguide layer may comprise a buffer layer, optical waveguides formed on the buffer layer and, in some implementations, additional structures such as portions of spacer structures, portions of alignment structured, electrical interconnects, portions of MEMS actuator, and the like. In some such cases, the buffer layer, which mechanically supports the optical waveguides and other structures fabricated thereon, may be referred to as a support layer. In various embodiments, thickness of the waveguide layer can be smaller than 10 microns, smaller than 30 microns, smaller than 50 microns, smaller than 70 microns or smaller than 100 microns.

[0120] In some embodiments, an IOCS device may comprise one or more optical ports optically coupled to one or more waveguides of the IOCS and configured to couple light

from an external waveguide (e.g., an optical fiber) or device to the one or more waveguides of the IOCS device. In various implementations, the optical ports may be disposed or formed on the first waveguide layer, second waveguide layer, or both.

[0121] In some embodiments, an IOCS device may comprise inter-layer optical couplers configured to vertically couple an optical port or waveguide on the first waveguide layer to an optical port or waveguide on the second waveguide layer. In some implementations, an interlayer optical coupler may comprise a first portion formed on the first waveguide layer and a second portion formed on the second waveguide layer, where the first portion is optically coupled to the second portion. In some other implementations, an inter-layer optical coupler may comprise a first portion formed on the first waveguide layer, a second portion formed on the middle waveguide layer, and a third portion formed on the third waveguide layer, where the first portion is optically coupled to the second portion, and the second portion is optically coupled to the third portion. In yet some other implementations, a portion of an inter-layer optical coupler can be a surface optical coupler, a grating coupler, a tapered waveguide, or a plurality of vertically stacked and optically coupled waveguides.

[0122] In some embodiments, an IOCS device may comprise alignment structures configured to facilitate or enable active or passive alignment of two wafers, which are bonded to form the IOCS device, during its fabrication. In some implementations, the first wafer may comprise a first plurality of alignment structures and the second wafer may comprise a second plurality of alignment structures associated with the first plurality of alignment structures. In some implementations, the alignment structures may be formed on the first and second waveguide layers. In some implementations, the alignment structures may be formed on a portion of wafer outside a region on which the IOCS device is formed (e.g., around the IOCS device and closer to an edge of each wafer). In some implementations, a first individual alignment structure of the first plurality of alignment structures may be paired with a second individual alignment structure of the second plurality of alignment structures. In various implementations, an alignment structure may comprise an optical waveguide portion, a pair of waveguide portions, one or a pair of surface optical couplers, a fiduciary mark, a protrusion, an opening, a groove, and the like. In various embodiments, alignment structure may comprise passive optical alignment structures, active optical alignment structures (collectively referred to as optical alignment structures), and self-alignment structures (referred to as physical

alignment structures). In some implementations, a first individual active alignment structure (e.g., on the first wafer) may comprise a pair of optically isolated waveguide portions, and the second individual active alignment structure (e.g., on the second waveguide layer) may comprise a waveguide structure configured to be optically coupled to the first individual active alignment structure when the two wafers are aligned. In some implementations, the first passive individual alignment structure (e.g., on the first waveguide layer) may comprise a first alignment mark and the second individual passive alignment structure (e.g., on the second waveguide layer) may comprise a second alignment mark configured to be matched or paired with the first individual passive alignment structure when the two wafers are aligned.

[0123] In some implementations, an individual self-alignment structure may comprise a protrusion, a pin, an opening, a hole, a V-groove, and the like. In some implementations, a first individual self-alignment structure (e.g., on the first wafer) may comprise a pin or protrusion, and a second individual self-alignment structure (e.g., on the second wafer) may comprise an opening or hole (e.g., a V-groove) configured to receive the pin such that when the pin is mechanically engaged with the opening the two wafers become aligned. More details about the application of alignment structures and the example alignment structures are described below.

[0124] Figures 6A and 6B schematically illustrate first (Figure 6A) and second (Figure 6B) side cross-sectional views of an example IOCS device 600 according to a first process architecture embodiment. The second cross-sectional side view can be rotated with respect to the first cross-sectional side view by 90 degrees (around an axis perpendicular to a major surface of the first substrate 602). The IOCS device 600 may comprise a first waveguide layer formed on the first substrate 602, a middle waveguide layer above the first waveguide layer and mechanically connected to the first substrate at least via a first plurality of anchors, and a second waveguide layer above the middle waveguide layer. Figures 6A and 6B show a first individual waveguide 302 of the first plurality of waveguides 102 (Figures 2A-2D), a second individual waveguide 304 of the second plurality of waveguides 104 (Figures 2A-2D), a shunt waveguide 306 of the plurality of shunt waveguides, a support layer 604 on which the second plurality of waveguides are formed, two anchors 605 of the first plurality of anchors, a switch anchor 508 of the plurality of switch anchors, and a lever beam (not shown) of the plurality of lever beams is also associated with an actuator). In the integration scheme

represented by Figure 6A, the first substrate 602 may comprise a top buffer sub-layer (not shown) on which the first waveguide 304 is formed.

[0125] The IOCS device 600 may be fabricated, as further detailed elsewhere in this specification, using an integration scheme where portions of an optical switch and/or an actuator are released after bonding the wafers (“post-bonding MEMS release process”). In this scheme, the first and second waveguides 302, 304 are first fabricated separately on respective substrates. The optical switch including the shut waveguide 306 is fabricated on the first substrate 602 having formed thereon the first waveguide 302. The components of the optical switch may be buried in a sacrificial material, e.g., an oxide that is etch-selective to the materials of the optical switch prior to bonding a second substrate (not shown) on which the second waveguide 304 is formed. In some examples, anchors 605 may be formed on first substrate 602 and buried in the sacrificial material. The second waveguide 304 may optionally also have formed thereon its own sacrificial material. After bonding the two substrates, the optical switch and/or the actuator may be released by removing the sacrificial material. Thereafter, the bulk of the substrate on which the second waveguide 304 may be removed, thereby leaving the support layer 604, which may be, e.g., a buried oxide of an SOI wafer. As described above, in this integration scheme, because the sacrificial material supporting the optical switch and/or the actuator spacers as well as additional bonding pads may provide sufficient mechanical support, the anchors may have smaller cross-sectional area or width relative to those of the spacers describe above, in the context of the pre-bonding MEMS release process.

[0126] In some embodiments, the IOCS device 600 may comprise alignment structures used during the fabrication process (e.g., for aligning the first substrate 602 and the second substrate). In some implementations, the alignment structures formed on the substrates or wafers used for fabricating the first embodiment (e.g., the IOCS device 600) may not include self-alignment structures.

[0127] In this first embodiment, the second waveguide layer of the IOCS device 600 comprises the support layer 604 that can be suspended by the second plurality of anchors 605 and mechanically connected the first substrate 602 via the second plurality of anchors 605 (two of which are shown). In such embodiments, a thickness and weight of the second waveguide layer, that includes the support layer 604 and the second plurality of waveguides,

may be configured such that it can be stably suspended and supported by the second plurality of anchors. For example, a thickness of the second waveguide layer or the support layer 604 may be smaller than an upper bound and/or the second waveguide layer may not be connected to or disposed on a substrate. In some implementations, the upper bound thickness of the second waveguide layer can be from 0.1 to 1 microns, from 1 to 2 microns, 2 to 10 microns, from 10 to 20 microns, from 20 to 30 microns, from 30 to 50 microns, from 50 to 100 microns, or from 200 to 800 microns. In some implementations the thickness of the second waveguide layer can be less than 800 microns. In some implementations, the thickness of the second waveguide layer can be smaller than 10 microns. In some embodiments, the second waveguide layer may consist of a support layer, a plurality of waveguides, alignment structures, and inter-level optical couplers formed on the support layer. In some implementations, an anchor of the second plurality of anchors may be attached to the first substrate and vertically extended away from the first substrate. In various embodiments, the anchor may have any cross-sectional shape including and not limited to circular, rectangular, oval, square, triangular, or the like. In some implementations, a cross-sectional area of an anchor can be less than 100 square microns, less than 10 square microns, or less than 1.0 square microns.

[0128] The first IOCS embodiment described above with respect to Figures 6A-6B may be fabricated using a first fabrication method. Referring to Figure 6C, the first fabrication method for fabricating the IOCS device 600 may comprise the following fabrication steps, according to embodiments:

[0129] The method 650 includes, at a first fabrication step comprising fabricating 652 a first waveguide layer and an optical switch structure on a first substrate 602. In some implementations, the first waveguide layer may be formed or disposed on the first substrate 602 and the optical switch structure may be formed or disposed on the first waveguide layer. In some implementations, an optical switch structure may comprise layers, regions, electrodes, and/or structures that may be used to form an optical switch at a waveguide crossing region upon performing one or more additional processes. In some implementations, the optical switch structure may be formed at least partially by forming a middle waveguide layer over the first waveguide layer. In some implementations, as fabricated, an optical switch structure may comprise a micromechanical structure, also referred to as microelectromechanical systems (MEMS) structure, and a shunt waveguide immobilized by a sacrificial material, e.g., an oxide

that is etch-selective against materials of the MEMS actuator and the optical switch. A MEMS structure may comprise layers and regions associated with a MEMS actuator. In some implementations, a MEMS structure may comprise a MEMS actuator embedded in a sacrificial layer that is etch selective such that the MEMS actuator can be released by etching the sacrificial layer. As such additional processes may be required to fabricate the optical switch (e.g., forming the MEMS actuator, suspending the shunt waveguide, removing a sacrificial layer, or other processes). These additional processes may be performed at a subsequent fabrication step after bonding the first substrate to a second substrate. In some implementations, the optical switch structure may comprise a shunt waveguide at least partly fixedly buried in a sacrificial material. In some implementations, the first waveguide layer may comprise, at least, a first plurality of bus optical waveguides 102 extending along a first direction from a first edge of the first substrate to the second edge of the first substrate. In some implementations, the first waveguide layer may further comprise one or more of a portion of an optical switch, a portion of an inter-layer optical coupler, a portion of an alignment structure, an electrode, an optical port, a portion of an anchor (e.g., shunt waveguide anchor and/or second layer anchor), and/or a bonding region or bonding pad. In some implementations, the first substrate may additionally comprise a portion of a mechanical stopper.

[0130] In some embodiments, at least some regions, areas, or volumes, within the first wafer may comprise a sacrificial layer or material. In some implementations, the sacrificial layer or material may be configured to temporarily support components of the optical switch. The sacrificial layer may also provide a surface on which the second waveguide layer is bonded. The anchors 605 may be formed before or after depositing the sacrificial material. In some embodiments, the anchors 605 can be formed after depositing the sacrificial material and may comprise vertical vias through the second waveguide layer and further through the sacrificial material. The anchors 605 (e.g., vertical vias) may serve as mechanical supports for the second waveguide layer (e.g. the support layer 604 and the second bus optical waveguide 304) that and maintain a vertical spacing (e.g., a predefined vertical spacing) between the first and second pluralities of waveguides. Additionally, in some embodiments, anchors 605 may provide electrical connections between the first and second waveguide layers. For example, an anchor of the anchors 605 may comprise a conductive line connecting a first electrical or optoelectronic component (e.g., an electrical device, a photodetector, a conductive pad, or a

conductive live line) disposed on or within the first waveguide layer to a second electrical or optoelectronic component on or within the second waveguide layer. In some implementations, the vertical vias formed of a material that is etch-selective to the sacrificial material removed from the gap between the first and second waveguide layers during a fabrication process.

[0131] In some implementations, the sacrificial layer may comprise an oxide or an organic or inorganic material that can be selectively removed without affecting the structural properties of the surrounding structures (e.g., bus waveguides, shunt waveguide, MEMS actuator, alignment structures, inter-layer couplers, optical ports and the like).

[0132] Still referring to Figure 6C, the method 650 additionally includes, at a second fabrication step, fabricating 654 a second waveguide layer on a second substrate (removed in Figures 6A and 6B). In some implementations, the second waveguide layer may comprise, a second plurality of bus optical waveguides extending in a second direction from a first edge of the second substrate to the second edge of the second substrate opposite to the first edge. In some implementations, the second direction can be substantially perpendicular to the first direction along which the first plurality of waveguides extend. In some implementations, the second substrate may further comprise an electrode, an optical port, a portion of an inter-layer optical coupler, a portion of an alignment structure, a portion of a mechanical stopper, and/or a bonding region or bonding pad. In some implementations, fabricating 654 of the second substrate may further comprise, an electrode, an optical port, a portion of an inter-layer optical coupler, a portion of an alignment structure, a portion of an anchor (e.g., shunt waveguide anchor, and/or second waveguide layer anchor), and/or a bonding region or bonding pad.

[0133] In some implementations, the second waveguide layer may comprise a support layer 604, which may be, e.g., a buried oxide layer of an SOI wafer. In some implementations, the second plurality of bus optical waveguides are formed on the support layer 604.

[0134] As mentioned above, the first and second substrates may include alignment structures for aligning prior to bonding. In some implementations, alignment structures may comprise passive alignment structures such as patterns (e.g., etched or protruded patterns) or marks (also referred to as fiducial marks) on both substrates (or dies). In some implementations, alignment structures may comprise active alignment structures configured

for active optical alignment of the two substrates. In some implementations, active alignment structures may comprise loop-back waveguide structures comprising waveguide sections on the first substrate and waveguide sections on the second substrates coupled by grating inter-layer couplers or tapered waveguide inter-layer couplers. In some implementations, two waveguide sections of an active alignment structure formed on the same substrate may be optically coupled to two optical ports on that substrate to allow transition measuring the optical transmission via the loop-back waveguide structure. Example embodiments of active alignment structures are shown in Figures 12A-12B and described in more detail elsewhere in this application. In some implementations, alignment structures may comprise self-alignment structures. A self-alignment structure may comprise a first portion (e.g., an opening or a female portion) on one substrate (e.g., the first substrate) and a second portion (e.g. a pin or a male portion) on the other substrate (e.g., the second substrate), where the first portion is configured to mechanically couple to the second portion by, e.g., receiving the first portion and cause the two substrates to be aligned. Several embodiments of self-alignment structures are shown in Figures 13A-13H, 14A-14G, and 15A-15C, and are described with more details below.

[0135] In some embodiments, fabricating the first and second substrates may comprise providing the first (or the second) substrate and forming the above-mentioned layers, features, and components on the first and second substrates using common microfabrication methods including but limited to methods of fabricating MEMS actuators and optical structures (e.g., waveguides, vertical couplers, tapered waveguides, and the like), semiconductor fabrication methods, and the like. In some implementations, the microfabrication methods may comprise lithographic mask or photoresist patterning, dry and wet etching, dielectric deposition, metal deposition, plating, and the like. In some implementations, the first and/or the second substrates may comprise a bulk substrate (e.g., a silicon substrate) or a multilayer substrate (e.g., silicon substrate having a top silicon-on-oxide layer (SOI), or silicon substrate having a top oxide layer).

[0136] Still referring to Figure 6C, the method 650 additionally includes at a third fabrication step, aligning 656 the first and second substrates for bonding (e.g., flip-chip bonding). Aligning 656 the first and second substrates may comprise aligning an optical switch formed on the first substrate to a bus optical waveguide of the second plurality of bus optical waveguides formed on the second substrate. In some embodiments, the first and second

substrates in aligning 656 may be aligned so that waveguide crossings are formed, and the shunt waveguides are properly aligned with respect to the respective waveguides of the second plurality of waveguides. In some implementations, properly aligning a shunt waveguide with respect to an individual waveguide of the second plurality of waveguides may comprise positioning and aligning the second end region (second coupling region) of the shunt waveguide below the individual waveguide such that once the fabrication is completed (e.g., MEMS actuator is released), actuating the corresponding optical switch optically couples the shunt waveguide to the individual waveguide based on a predetermined coupling strength. In some implementations, predetermined coupling strength may correspond to low loss optical coupling between the waveguides associated with the crossing region (e.g., an insertion loss less than 0.1 dB, less than 1dB, less than 2dB, or less than 3dB).

[0137] In some methods of the embodiments, aligning 656 may comprise passive alignment using passive alignment structures, active alignment using active alignment structures, self-alignment using self-alignment structures, or a combination thereof.

[0138] Example alignment methods compatible with the First Fabrication Method include one or more of the following alignment steps:

- 1) Passively aligning the first and second substrates using the passive aligning marks. For example, two matching marks each on one of the substrates may be aligned under a microscope by moving (e.g., translating and/or rotating) one substrate with respect to the other.
- 2) Actively aligning the passively aligned first and second substrates by providing light to a first portion of an active alignment structure on one of the substrates via an optical port (e.g., from an external optical fiber via a fiber coupler) and measuring light looped back via a second portion of the active alignment structure on the other of the substrates. In some implementations, an external laser or emitting diode may be used to provide light and a photodetector may be used to measure and monitor the power of output light. In some implementations, the photodetector can be an external photodetector. In some implementations, the output light may be coupled to and measured by a photodetector integrated on the first or the second substrate. Next, one substrate may be moved (e.g., translated and/or rotated) with respect to the other while monitoring the optical output power until the optical output power reaches a threshold value. In

some embodiments, optical power through two or more active alignment structures may be simultaneously and/or sequentially monitored. In some implementations, the two or more active alignment structures may be positioned at different corners of both substrates. In some implementations, two sets of active alignment structures may be located on two corners of both substrates for rotation alignment. In some implementations, two active alignment structures may be configured for alignment along two substantially perpendicular directions parallel to a major surface of the first and/or the second substrates. In some implementations, an active alignment comprising a grating inter-layer coupler (e.g., a grating coupler) may be used for coarse alignment. In some implementations, an active alignment structure comprising a tapered waveguide inter-layer coupler may be used for fine tuning. Accordingly, the alignment process may comprise a coarse alignment step and a fine alignment step. In some implementations, a tapered waveguide inter-layer coupler may comprise at least two tapered waveguide portions each portion fabricated on one of the first and second substrates and having a tapered end. When the tapered end of one tapered waveguide portion is aligned with the taper end of the other tapered waveguide portion, light can couple from one tapered waveguide portion to the other one.

[0139] In some implementations, the alignment process described above may begin by a self-alignment procedure where portions of three or more self-alignment structures on the first and substrates are aligned and then engaged to initially align the two substrates prior to passive alignment. In some implementations, the self-alignment step may be performed after passive alignment and before active alignment. In some implementations, an alignment process may skip the first or second alignment steps above, change the order of these steps, or include additional steps.

[0140] In some implementations, the alignment structures are configured such that performing any of the alignment processes described above result at least in alignment (e.g., simultaneous alignment) of portions of inter-layer optical couplers on the two substrates, and/or alignment of the shunt waveguides to respective waveguides of the second plurality of waveguides.

[0141] Still referring to Figure 6C, the method 650 additionally includes a fourth fabrication step, comprising bonding 658 the first substrate, that is aligned with respect to the

second substrate, to the second substrate using one of any suitable flip-chip bonding or wafer bonding methods. The first and second substrates may be face-to-face bonded, where one or both of the substrates may have formed on a face thereof a sacrificial material that may contact the opposing face at the time of bonding. In some implementations, the bonding may occur between bonding regions and pads provided on both substrates, which may be adapted for direct bonding as described above. In some implementations, bonding 658 may comprise bonding the first substrate 602 to the second substrate by bonding a front surface of a second wafer to a front surface the first wafer where the front surface of the first wafer comprises the sacrificial material. In some implementations, a vertical spacing between the first and second substrates and thereby the first and second bus optical waveguides is established by a sacrificial layer formed on the first substrate.

[0142] Still referring to Figure 6C, the method 650 additionally includes a fifth fabrication step, which comprises removing 660 the second substrate from the second waveguide layer. Removing 660 the second substrate may include back-grinding, dry etching and/or wet etching to thin down the second substrate to a suitable thickness. In one example, where the second substrate is an SOI wafer on which the second waveguide layer is formed, the bulk portion of the SOI wafer may be removed by grinding and wet etching and stopping on the buried oxide.

[0143] Still referring to Figure 6C, the method 650 additionally includes a sixth fabrication step, which comprises processing 662 the layers between the first and second substrates (e.g., between the first and second waveguide layers) to release the MEMS actuators, form the optical switches, release the shunt waveguides, form a anchors that support the shunt waveguide, and/or form a plurality of anchors that hold and/or support the second waveguide layer above the first waveguide layer. In some implementations, forming the plurality of anchors that hold and/or support the second waveguide layer may comprise forming a plurality of vertical vias through the second waveguide layer and further through the sacrificial material. These vertical vias may serve as mechanical anchors that secure the second waveguide layer (e.g. the support layer 604 and the second bus optical waveguides formed thereon) to the first substrate 602 or the first wafer and maintain a vertical spacing (e.g., a predefined vertical spacing) between the first and second pluralities of waveguides. In some embodiments, an anchor that supports the second waveguide layer may provide electrical connections between

the first and second waveguide layers. In some implementations, an anchor that supports the second waveguide layer may comprise a conductive via. In some implementations, an anchor that supports the second waveguide layer may comprise a conductive via may comprise a dielectric region. In some such examples, the anchor may comprise a conductive line extending from the first waveguide layer to the second waveguide layer via the dielectric region.

[0144] In some implementations, processing these layers may further comprise suspending a shunt waveguide and/or suspending the second waveguide layer. A resulting optical switch may comprise the suspended shunt waveguide and MEMS actuators configured such that, upon actuation, they optically couple first and second end regions of the suspended shunt waveguide to a bus optical waveguide (e.g., bus optical waveguide 302) of the first plurality of bus optical waveguides and a waveguide (e.g., bus optical waveguide 304) of the second plurality of bus optical waveguides, respectively.

[0145] Figures 7A and 7B schematically illustrate first (7A) and second (7B) side cross-sectional views of an example IOCS device 700 according to a second process architecture embodiment. The second cross-sectional side view can be rotated with respect to the first cross-sectional side view by 90 degrees (around an axis perpendicular to a major surface of the first substrate 602). The IOCS device 700 may comprise a first waveguide layer formed on the first substrate 602, a middle waveguide layer above the first waveguide layer and mechanically connected to the first substrate at least via a first plurality of anchors, and a second waveguide layer above the middle waveguide layer and formed on a second substrate 704. Figures 7A and 7B show a first individual waveguide 302 of the first plurality of waveguides 102 (Figures 2A-2D), a second individual waveguide 304 of the second plurality of waveguides 104, a shunt waveguide 306 of the plurality of shunt waveguides, a second substrate 704 on which the second plurality of waveguides are formed, a switch anchor 508 of the plurality of switch anchors, and mechanical stoppers comprising mechanical stopper portions 702a and 702b. In the integration scheme represented by Figure 7A, a first substrate 602 may comprise a top buffer sub-layer (not shown) on which the first waveguide 302 is formed and the second substrate 704 may comprise a top buffer sub-layer (not shown) on which the second waveguide 304 is formed.

[0146] The IOCS device 700 may be fabricated, as further detailed elsewhere in the application, using an integration scheme where at least portions of an optical switch and/or

an actuator are released prior to bonding the wafers (“pre-bonding MEMS release process”). In this scheme, the first and second waveguides 102, 104 are first fabricated separately on respective substrates 602, 704. The optical switch including the shunt waveguide 306 is fabricated on the first substrate 602 having formed thereon the first waveguide 302. In a similar manner as the integration scheme described above with respect to Figures 6A and 6B, the components of the optical switch on may initially be buried in a sacrificial material, e.g., an oxide that is etch-selective to the materials of the optical switch. The second waveguide 304 may also be formed with a sacrificial material. However, unlike the integration scheme described with respect to Figures 6A and 6B, prior to bonding the first and second substrate 602, 704, the sacrificial materials are removed from both substrates 602, 704. That is, prior to bonding the two substrates, the optical switch and/or the actuator may be released by removing the sacrificial material. As described above, in this integration scheme, because sacrificial materials are removed from both substrates, mechanical stoppers portions 702a, 702b may be the primary mechanical structures that come into contact and bonded to each other. As such, the spacers may have substantial cross-sectional area or width to provide sufficient mechanical support during and after the bonding process.

[0147] In some embodiments, the IOCS device 700 may comprise alignment structures used during the fabrication process (e.g., for aligning the first substrate 602 and the second substrate 704). In some implementations, the alignment structures formed on the substrates or wafers used for fabricating the first embodiment may comprise passive alignment structures, active alignment structures, self-alignment structures, or a combination thereof.

[0148] In this this second embodiment, the second waveguide layer of the IOCS device 700 is suspended and supported by the second substrate 704 that is bonded to the first substrate 602 via a first and second pluralities bonding regions or bonding pads formed on the first and second substrates 602, 704, respectively, and can also be bonded at other regions. In some embodiments, the second waveguide layer may be formed on the second substrate 704. In some implementations, a thickness of the second substrate can be larger than 100 microns, larger than 500 microns, larger than 700 microns, larger than 1000 microns, or larger values. In some implementations, the IOCS device 700 may comprise a plurality of mechanical stoppers (also referred to as spacers) 702 configured to define or establish a vertical separation between the first and second substrates 602, 704, and thereby the first and second pluralities

of waveguides. In some embodiments, each mechanical stopper may comprise a first stopper portion 702a connected to the first substrate 602 and a second mechanical stopper portion 702b connected to the second substrate 704. In some implementations, the ends of the first and second stopper portions 702a, 702b, that are opposite to the respective substrates may be in mechanical contact or bonded. In some implementations, the plurality of mechanical stoppers may be formed by contacting a first plurality of stopper portions 702a formed on the first substrate 602 with a second plurality of stopper portions 702b formed on the second substrate 704. In various embodiments, a stopper portion may have any cross-sectional shape including and not limited to circular, rectangular, oval, square, triangular, or the like. In some implementations, a cross-sectional area of a mechanical stopper can be larger than 10, or larger than 100, larger than 500 square microns or within any ranges formed by these values or larger or smaller values. In some embodiments, the first plurality of the bonding regions or pads may comprise the first plurality of stopper portions and the second plurality of the bonding regions or pads may comprise the second plurality of stopper portions.

[0149] In some embodiments, the IOCS device 700 may comprise one or more conductive lines connecting a first electrical or optoelectronic component (e.g., an electrical device, a photodetector, a conductive pad, or a conductive live line) disposed on or within the first waveguide layer or on the first substrate 602 to a second electrical or optoelectronic component on or within the second waveguide layer or on the second substrate 704. In some implementations, the conductive line may be formed by the first and second stopper portions 702a, 702b.

[0150] The second IOCS embodiment described above with respect to Figures 7A-7B may be fabricated using a second fabrication method. Referring to Figure 7C, the second fabrication method 750 for fabricating the IOCS device 700 may comprise the following fabrication steps, according to embodiments:

[0151] Second fabrication method 750 includes, at a first fabrication step, fabricating 754 a first waveguide layer and an optical switch structure on a first substrate 602. In some implementations, the first waveguide layer formed or disposed on the first substrate 602 and the optical switch structure may be formed or disposed on the first waveguide layer. In some implementations, an optical switch structure may comprise one or more features described above with respect to the first fabrication method.

[0152] In some implementations, the first waveguide layer may comprise, at least, a first plurality of bus optical waveguides 102 extending along a first direction from a first edge of the first wafer to the second edge of the first wafer. In some such cases, the first waveguide layer may further comprise one or more of a portion of an optical switch, a portion of an anchor, a portion of an inter-layer optical coupler, a portion of an alignment structure, and a bonding region or bonding pad. In some implementations, the first substrate may further comprise, an electrode, an optical port, a portion of an inter-layer optical coupler, a portion of an anchor (e.g., shunt waveguide anchor), a portion of an alignment structure, and/or a bonding region or bonding pad. In some implementations, the first wafer may comprise a portion of a mechanical stopper.

[0153] Still referring to Figure 7C, the method 750 additionally includes, at a second fabrication step, which comprises processing 756 the layers and structures formed on the first substrate to release the MEMS actuators and form the optical switches. In some implementations, processing the layers may further comprise suspending the shunt waveguides. A resulting optical switch may comprise a suspended shunt waveguide 306 and MEMS actuators configured such that, upon actuation, they optically couple a first end region of the suspended shunt waveguide 306 to a bus optical waveguide (e.g., bus optical waveguide 302) of the first plurality of bus optical waveguides and a second end region of the suspended shunt waveguide to a second bus optical waveguide above the optical switch (e.g., bus optical waveguide 304).

[0154] Still referring to Figure 7C, the method 750 additionally includes, at a third fabrication step, fabricating 758 a second waveguide layer on a second substrate 704. In some implementations, the second waveguide layer may comprise a second plurality of bus optical waveguides extending in a second direction from a first edge of the second substrate to the second edge of the second substrate opposite to the first edge. In some implementations, the second direction can be substantially perpendicular to the first direction along which the first plurality of waveguides extend. In some implementations, the second substrate may further comprise, an electrode, an optical port, a portion of an inter-layer optical coupler, a portion of an alignment structure, a portion of a mechanical stopper, and/or a bonding region or bonding pad.

[0155] In some implementations, and as a part of method 750, the second waveguide layer may comprise a buffer layer and a second plurality of bus optical waveguides formed on the buffer layer. The second plurality of bus optical waveguides may extend along a second direction from a first edge of the second substrate to the second edge of the second substrate. In some implementations, the second direction can be substantially perpendicular to the first direction along which the first plurality of waveguides extend. In some implementations, the second waveguide layer may further comprise, an optical port, a portion of an inter-layer optical coupler, a portion of an alignment structure, and/or a bonding region or bonding pad. In some implementations, the alignment structures may comprise features and structures described above with respect to the first fabrication method. Similarly, the first, and third fabrication steps, fabricating 754 and fabricating 758, may comprise one or more features described above with respect to first and second fabrication steps of the fabrication method described above with respect to Figure 6C.

[0156] Still referring to Figure 7C, the method 750 additionally includes a fourth fabrication step, which comprises aligning 760 the first and second substrates for bonding (e.g., flip-chip bonding). Aligning 760 may comprise aligning the optical switches formed on the first substrate to the and the second waveguides formed on the second substrate. In some embodiments, the first and second substrates may be aligned so that waveguide crossing are formed, and the shunt waveguides are properly aligned with respect to the respective waveguides of the second plurality of waveguides. In some implementations, a properly aligning a shunt waveguide with respect to an individual waveguide of the second plurality of waveguides may comprise positioning and aligning the second end region (second coupling region) of the shunt waveguide below the individual waveguide such that actuating the corresponding optical switch optically couples the shunt waveguide to the individual waveguide based on a predetermined coupling strength. In some implementations, predetermined coupling strength may correspond to low loss optical coupling between the waveguides associated with the crossing region (e.g., an insertion loss less than 0.1 dB, less than 1dB, less than 2dB, or less than 3dB).

[0157] In some embodiments, the alignment process may comprise passive, alignment, active alignment, self-alignment, or a combination thereof based on the example alignment method described above with respect to Figure 6C. In some implementations, the

alignment process described above may begin by a self-alignment procedure where portions of three or more self-alignment structures on the first and substrates are aligned and then engaged to initially align the two substrates prior to passive alignment. In some implementations, the self-alignment step may be performed after passive alignment and before active alignment. In some implementations, an alignment process may skip the first or second alignment steps above, change the order of these steps, or include additional steps.

[0158] In some implementations, the alignment structures are configured such that performing any of the alignment processes described above result, at least, in alignment (e.g., simultaneous alignment) of portions of inter-layer optical couplers on the two substrates, and the shunt waveguides to the second plurality of waveguides.

[0159] In some implementations, the alignment structures are configured such that performing any of the alignment processes described above result, at least, in alignment (e.g., simultaneous alignment) of portions of the inter-layer optical couplers on the two substrates, alignment of the shunt waveguides to respective waveguides of the second plurality of waveguides, alignment of respective portions of the bonding regions (or pads) on the two substrates, and/or alignment of respective portions of the mechanical stoppers on the two substrates.

[0160] Still referring to Figure 7C, the method 750 additionally includes, at a fifth fabrication step, bonding 762 the first substrate 602, which is aligned with respect to the second substrate 704, to the second substrate 704 using common flip-chip bonding methods. In some implementations, the bonding may occur between bonding regions and pads provided on both substrates. In some implementations, bonding 762 may comprise bonding the first substrate 602 to the second substrate 704 by bonding a front surface of a second wafer to a front surface a first wafer.

[0161] In some implementations, the mechanical stoppers may establish a predefined vertical spacing between the first and second waveguide layers and thereby the vertical spacing between the first and second pluralities of waveguides. For example, a first stopper portion 702a connected to the first substrate 602 may mechanically contact a second stopper portion 702b connected to the second substrate 704 to form a mechanical stopper 702 extending from a top surface of the first substrate 602 (or the first waveguide layer) to a top surface of the second substrate 704 (or the second waveguide layer). The height of the resulting

mechanical stopper, which can be substantially equal to vertical spacing (e.g., a predefined vertical spacing) between the two waveguide layers, can be from 0.5 microns to 1 micron, from 1 micron to 3 microns, from 3 microns to 7 microns, from 7 microns to 10 microns, or larger values. In some implementations, the bonding regions and/or pads may comprised the stopper portion on both substrates. In some such cases, the ends of the first and second stopper portions 702a, 702b, opposite to the respective substrates may be bonded during the bonding process.

[0162] As described above, the first and second IOCS embodiments described above with respect to Figures 6A-6B and Figures 7A-7B may be fabricated using at least two different fabrication methods including “pre-bonding MEMS release process” and “post-bonding MEMS release process” methods described herein. The two different fabrication methods may both comprise a first step of fabricating a first wafer (wafer 1) or die, a second step of fabricating a second wafer (wafer 2) or die separate from the first wafer or die, a third step of aligning the first and second wafers or dies, and a fourth step of bonding the two wafers or dies. The first fabrication method is different from the second fabrication method in that the first fabrication method includes at least two additional steps (e.g., fifth and sixth fabrication steps described herein) after the fourth step and the first fabrication step of the first fabrication method may omit certain processes (e.g., a MEMS actuator release process described herein) that are performed after fourth fabrication step (e.g., during the sixth fabrication step described herein).

[0163] In some embodiments, the bus optical waveguides (herein referred to as waveguides), optical ports (e.g., fiber-to-chip couplers), inter-layer optical couplers (e.g., tapered waveguide or grating couplers), MEMS actuators or MEMS structures, mechanical stoppers, electrodes and electrical connections, and other structures are first fabricated separately on the first and/or second wafers. In some embodiments, the first plurality of waveguides, the shunt waveguides and the MEMS actuators may be fabricated on the first wafer and the second plurality of waveguides may be fabricated on the second wafer. In some implementations, after complete or partial fabrication of one of more these structures and components, the two wafers may be aligned and bonded (e.g., flip-chip bonded) with each other. In one embodiment, the two fabricated wafers are bonded by wafer-scale bonding methods. In another embodiment, the two fabricated wafers are first diced into chips (or dies), and the chips from the first wafer and respective chips from the second wafer are bonded, e.g.,

by precision assembly procedures. In some embodiments, the vertical spacing between the first and second wafers may be kept by mechanical stopper portions fabricated on one or both wafers.

[0164] In some embodiments, the alignment methods and processes described above may be generally used for aligning two wafers or two substrates each comprising an integrated photonic circuit or a portion of an integrated photonic circuit. In some implementations, processes described above may be used to fabricate optical devices and/or optical device portions on different substrates or wafers or on two or more substrates or wafers. In some implementations, these optical devices and/or optical device portions may not have any movable region(s). In some implementations, these optical devices and/or optical device portions may not include a MEMS actuator. In some implementations, processes described above may be used to evanescently couple optical devices and/or optical device portions fabricated on different substrates or wafers or on two or more substrates or wafers.

[0165] In various implementations, fabricating the first and second waveguide layers (e.g., fabricating 652, 654, 754, and 758 of fabrication methods 650 and 750) may comprise lithographically patterning to form an optical bus waveguide extending within the waveguide layer on a front side of a substrate. In some implementations, the patterning may comprise depositing a mask layer over an unstructured waveguide layer, lithographically patterning the mask, and etching (e.g., dry or wet etching) the exposed portion of the unstructured waveguide layer to form the waveguide layer comprising optical structures (e.g., bus optical waveguides, optical alignment structures) or other structures.

[0166] In some implementations, fabricating the first and second waveguide layers may further comprise forming alignment structures, electrical contacts, portions of a MEMS actuator, portions of an optical switch, bonding regions, portions of a mechanical spacer, or a portion of an anchor (e.g., an anchor supporting a shunt waveguide or the second waveguide layer). In some implementations, the alignment structures may comprise waveguide structures and/or sections such as an optically isolated pair of optical waveguides (e.g., substantially parallel optical waveguides), a portion of an inter-layer coupler (e.g., a grating coupler, a tapered waveguide coupler, or the like), a loop-back waveguide structure (e.g., a U-shape waveguide section).

Optical Port Arrangements

[0167] As described above with respect to Figures 2A-2D an IOCS device such the IOCS device 200, 201, 202, 203 may comprise two waveguide layers and a plurality of optical ports configured to optically couple bus optical waveguides to external optical components such as optical fiber waveguides. In various embodiments, all of the optical ports may be formed (or disposed) on one of the two waveguide layers of the IOCS device or may be distributed between the two waveguide layers. For example, referring back to Figures 2A-2D, the first plurality of optical ports 106 (optical port group "A") and the third plurality of the optical ports 112 (optical port group "B") may be located on the same wafer or on different wafers. In some implementations, e.g., when all optical ports are located on one of the waveguide layers, the bus optical waveguides formed on the other waveguide layer may be optically coupled to some of the optical ports via inter-layer couplers (e.g., grating or tapered waveguide couplers). In some embodiments, a tapered waveguide inter-layer optical coupler may comprise one or more stages of adiabatic waveguide couplers formed between two tapered waveguide ends. As an example of such tapered waveguide interlayer optical coupler is shown in Figures 11A-11C. and described below.

[0168] In some embodiments, the optical ports may comprise fiber-to-waveguide couplers (also referred to as fiber-to-chip or fiber couplers) used to couple light between one or more external optical fibers to the bus optical waveguide of the IOCS device. In various embodiments, the fiber couplers may comprise surface optical couplers (e.g., grating couplers), edge couplers, evanescent couplers, microlens couplers, and other types of suitable optical couplers.

[0169] Figures 8A-8D schematically illustrate top views (8A-8B) of the first and second substrates (or wafers) 602, 704 used to fabricate an example IOCS device (e.g., IOCS device 200 shown in Figure 2A) and the side views (8C-8D) of the resulting IOCS device. In this example, all the optical ports 206 are located on the second substrate 704 and the first plurality of waveguides 102 are optically coupled to the respective optical ports on the second substrate 704 via a plurality of inter-layer optical couplers 802. The plurality of the inter-layer optical couplers 802 may comprise first plurality of inter-layer coupler portions 802a formed or disposed on the first substrate 602 and a second plurality of inter-layer coupler portions 802b formed or disposed on the second substrate 704. In the example shown, a first group of

inter-layer couplers 802 are placed between the first plurality of optical ports (“A1”, “A2”, ... , “Am”) 106 on the second substrate 704 and first ends of the corresponding bus optical waveguides of the first plurality of bus optical waveguides 102 on the first substrate 602 and a second group of inter-layer couplers 802 are placed between the second plurality of optical ports (“C1”, “C2”, ... , “Cm”) 108 on the second substrate 704 and second ends of the corresponding first plurality of bus optical waveguides 102 on the first substrate 602.

[0170] Figures 9A-9D schematically illustrate top views (9A-9B) of the first and second substrates (or wafers) 602, 704 used to fabricate an example IOCS device (e.g., IOCS device 201 shown in Figure 2B) and the side views (9C-9D) of the resulting IOCS device. In this example, all the optical ports 206 are located on the first substrate 602 and the second plurality of waveguides 104 are optically coupled to the respective optical ports on the first substrate 602 via a plurality of inter-layer optical couplers 802. The plurality of the optical couplers 802 may comprise first plurality of inter-layer coupler portions 802a formed or disposed on the first substrate 602 and a second plurality of inter-layer coupler portions 802b formed or disposed on the second substrate 704. In the example shown, a first group of inter-layer couplers 802 are placed between the third plurality of optical ports (“B1”, “B2”, ..., “Bm”) 112 on the first substrate 602 and first ends of the corresponding bus optical waveguides on the second substrate 704. In the examples shown, second ends of the first and second pluralities of waveguides 102, 104 may be optically connected to optical devices and components formed or disposed on one or both of the first and second substrates.

[0171] Figures 10A-10D schematically illustrate top views (10A-10B) of the first and second substrates (or wafers) 602, 704 used to fabricate an example IOCS device (e.g., IOCS device 200 shown in Figure 2A) and the side views (10C-10D) of the resulting IOCS device. In this example, the first plurality of optical ports 106 are located on the first substrate 602 and the third plurality of optical ports 112 are located on the second substrate 704. As such this IOCS device does not include any inter-layer optical coupler configured to optically couple a waveguide to an optical port. The first plurality of waveguides 102 are directly connected to the first plurality of optical ports 106 and the second plurality of waveguides 104 are directly connected to the third plurality of optical ports 112.

[0172] In the examples shown in Figures 8C-8D, 9C-9D, and 10C-10D, a shunt waveguide 806 is actuated to couple a bus optical waveguide formed on the first substrate 602

to a bus optical waveguide on the second substrate 704 and other shunt waveguides 804 are in a neutral position optically decoupled from the bus optical waveguides of the first and second substrates 602, 704.

[0173] In some embodiments, the pitch of a plurality of optical ports 206 and, in some implementations, the pitch of the respective waveguides can be chosen to be substantially equal to the pitch of an optical fiber array coupled to the plurality of the optical ports. In some embodiments, the pitch of a plurality of waveguides can be smaller than that of the optical fiber array. The density of the waveguides and corresponding optical switch matrix can be greater than that of the optical fiber array.

Inter-Layer Couplers

[0174] In various embodiments, an IOCS device (e.g., IOCS device 200, 201, 202, or 203) may comprise one or more inter-layers optical couplers configured to optically connect a waveguide or a waveguide section on a first waveguide layer to a second waveguide layer vertically separated from the first waveguide layer. In some implementations, an interlayer optical coupler can be optically connected to a waveguide section forming an active alignment structure. In some implementations, an inter-layer waveguide coupler can be optically connected to an individual waveguide on one of the waveguide layers of the IOCS device and optically connect the individual waveguide to an optical port located on the other waveguide layer of the IOCS device. In yet other examples, an inter-layer waveguide coupler can be optically connected to an individual waveguide on one of the waveguide layers of the IOCS device to optically connect the individual waveguide to another waveguide or an optical device located on the other waveguide layer of the IOCS device.

[0175] In some embodiments, an inter-layer optical coupler (also referred to as inter-layer coupler) may comprise a first portion on a first substrate or waveguide layer, and a second portion on a second substrate or waveguide layer, where the first and second portions are optically coupled via free-space or guided light propagation, or evanescent coupling. In some implementations, the two portions of an inter-layer coupler can be substantially similar or different.

[0176] In some embodiments, each portion of an inter-layer coupler (e.g., a grating inter-layer coupler) may comprise a surface coupler (e.g., a grating coupler) configured to

transform light received from a waveguide on a waveguide layer to light (e.g., a beam of light) propagating away from the waveguide layer in a vertical direction perpendicular to a major surface of the waveguide layer and couple light (e.g., a light beam emitted from another surface coupler) normally incident on the waveguide layer to the waveguide.

[0177] In some embodiments, each portion of an inter-layer coupler (e.g., a tapered waveguide inter-layer coupler) may comprise a coupler waveguide section having a first end optically connected to a bus optical waveguide or a waveguide section of an active alignment structure and a second end, a coupling end, configured to be evanescently coupled to another coupler waveguide section positioned vertically above the coupler waveguide section. In some implementations, the coupling end of the coupler waveguide section may comprise a tapered end having a width that is tapered down from a first width (e.g., the width of the bus optical waveguide) to second width smaller than the first width. In some implementations, the second width can be 50%, 25%, 10% of the first width or smaller. Advantageously, when the two coupling ends are evanescently coupled, the resulting coupling junction (an adiabatic coupling junction) can transfer light from one waveguide coupler section to another waveguide coupler section. Figures 11A-11C schematically illustrate a top view (Figure 11A), a side view (Figure 11B), and a perspective view (Figure 11C) of an example tapered waveguide inter-layer coupler comprising a first coupler waveguide section 802a and a second coupler waveguide section 802b both having a tapered coupling end. In some implementations, the waveguide section 802a and a second coupler waveguide section 802b can be substantially parallel to each other. In some embodiments, the first coupler waveguide section 802a is formed on a first waveguide layer and the second coupler waveguide section 802b is formed on a second waveguide layer vertically separated from the first waveguide layer. The first coupler waveguide section 802a may be aligned with respect to the second coupler waveguide section 802b such that one tapered end is above the other tapered end and the two tapered ends longitudinally and laterally overlap. In some implementations, larger than 20%, 50%, or 90%, or a percentage defined by any of these values, of the tapered portions may longitudinally overlap. In some implementations, a vertical separation between the first and second coupler waveguide sections 802a, 802b can be from 10% to 200% of the wavelength of light coupled by the tapered waveguide inter-layer coupler. In some implementations, the optical insertion loss between the two evanescently coupled waveguide sections 802a, 802b, can be very

sensitive to lateral (along y-axis) and longitudinal (along x-axis) alignment between the first and second coupler waveguide sections 802a, 802b. As such, tapered waveguide inter-layer couplers may be used for fine alignment between the first and second substrate during fabrication process an IOCS device. In some implementations, the insertion loss of a grating inter-layer coupler can be less sensitive to the lateral and longitudinal alignment between the two vertically separated grating portions compared to a tapered waveguide inter-layer coupler. As such, grating inter-layer couplers may be used for coarse alignment between the first and second substrate during fabrication process an IOCS. In some implementations, the optical insertion loss between the two evanescently coupled waveguide sections 802a, 802b, can be less sensitive to longitudinal alignment between the first and second coupler waveguide sections 802a, 802b compared to lateral alignment between them. As such, lateral alignment with tapered waveguide inter-layer coupler can be more precise than longitudinal alignment. In some implementations, the two substrates (or wafers) of an IOCS device may include portions of tapered waveguide inter-layer couplers oriented in two perpendicular directions to allow precise two-dimensional alignment.

Active Alignment Structures

[0178] As described above, during fabrication process on an IOCS device, two wafers or chips may be aligned such that after bonding and formation of the IOCS device, optical switches and inter-layer couplers can couple light between the waveguides on different waveguide layers or waveguides and ports on different layers with low insertion loss. It is also possible that one or both wafers may be divided into separate sections or parts or singulated and, then, aligned and bonded.

[0179] In some implementations, the two wafers or chips may comprise active alignments structures configured such that maximizing transmitted optical power via active alignments structures results in optical coupling with low optical insertion loss via the shunt waveguides and the inter-layer couplers. In some embodiments, a pair of active alignment structures may be used to actively align the two wafers or substrates.

[0180] In some embodiments, active alignment structures may comprise loop-back waveguide structures with waveguide sections on both wafers coupled by inter-layer couplers (e.g. grating couplers and tapered waveguide). In some implementations, optical ports (e.g.,

fiber couplers) on one of the substrates or wafers may be used to input light to loop-back waveguide structures, and couple output light to external detectors. When light is input to a loop-back structure and optical power transmitted via the loop-back waveguide structure, active optical alignment between the two wafers or substrates can be performed by substantially maximizing the monitored optical power. In some embodiments, loop-back waveguide structures comprising grating inter-layer couplers may be used for coarse alignment, and loop-back waveguide structures comprising tapered waveguide inter-layer couplers in two directions (e.g., two perpendicular directions such as x-direction and y-direction) may be used for fine alignment. In some embodiments, at least two sets of active alignment structures may be located on at least two corners of the each one of the substrates for rotation alignment.

[0181] In some implementations, a first active alignment structure of the pair may be formed of the first substrate and the second active alignment structure of the pair may be formed of the second substrate. In some implementations, the first active alignment structure may comprise two optically isolated elements (e.g., two waveguide portions or two surface couplers). Light may be provided from a light source (e.g., a laser or an LED) to a first element of the first active alignment structure and light output from a second element may be measured using a photodetector while the second active optical alignment structures is moved above the first active alignment structure (e.g., by moving the second substrate above the first substrate). When aligned to the first active alignment structure, the second active alignment structure may receive light from one element of the first active alignment structure and transmit the received light to the second element of the first active alignment structure. As such, when the first and second active alignment elements are aligned (e.g., laterally and longitudinally aligned), the optical power received from the second element of the first active alignment element can be above a threshold value, e.g., at a maximum or near maximum level.

[0182] In some embodiments, the self-alignment structures may be formed on regions of major surface of a substrate different from region(s) over which the layers and/or structures associated with the waveguides, optical switches, and inter-layer couplers, and optical ports are fabricated.

[0183] Examples of active alignment structures are shown in Figures 12A-12C. Figure 12A schematically illustrates a top view of a first substrate or wafer comprising a first

optical switch region 1200a where elements of an IOCS device are fabricated, and a first surrounding region where first portions of active alignment structures are fabricated. In some implementations, the first surrounding region and the first optical switch region 1200b are non-overlapping. Figure 12A schematically illustrates a top view of a second substrate or wafer comprising a second optical switch region 1200b where elements of an IOCS device are fabricated, and a second surrounding region, where second portions of active alignment structures are fabricated. In some implementations, the second surrounding region and the second optical switch region 1200b are non-overlapping. Figure 12C schematically illustrates a see-through top view of the IOCS device formed by overlapping the first and second substrates when the active alignment structures on the two wafers are aligned to increase or maximize the optical power transmitted via one or more pairs of the active alignment structures.

[0184] In the example shown, two sets of active alignment structures are located at two corners of each one of the first and second substrates 602, 704 to rotationally and translationally align the first and second substrates 602, 704. Each set of active alignment structures can optically communicate with external optical sources and detectors via a set of optical ports 1207 (e.g., fiber-to-waveguide optical couplers). In this example, each set of active alignment structures comprise first loop-back waveguide structures 1202a/b for coarse alignment, and second and third loop-back waveguide structure 1204a/b, 1206a/b for fine alignment in longitudinal (e.g., along x-axis) and lateral (e.g., along y-axis) directions. Additionally, each set of active alignment structures includes a single waveguide loop 1208 for optically characterizing the waveguides, waveguide sections, and the optical ports. The first loop-back waveguide structure 1202a/b comprises a first element 1202a comprising a pair of grating couplers connected via a waveguide section, and a second element 1202b comprising a pair of optically isolated waveguides each extending from an optical port to a grating coupler. The second loop-back waveguide structure 1204a/b comprises a first element 1204a comprising a pair of tapered waveguide couplers extending along x-direction and connected via a waveguide section, and a second element 1204b comprising a pair of optically isolated waveguides each extending along x-direction from an optical port to a tapered waveguide coupler. The second loop-back waveguide structure 1206a/b comprises a first element 1206a comprising a pair of taper waveguide couplers extending along y-direction and connected via

a waveguide section, and a second element 1206b comprising a pair of optically isolated waveguides each extending along y-direction from an optical port to a tapered waveguide coupler.

[0185] As mentioned above, in some embodiments, active alignment may comprise a first step of coarse alignment using the grating inter-layer coupler loop-back waveguides (first loop-back waveguide structure 1202a/b) followed by a second step of fine alignment using the tapered waveguide inter-layer coupler loop-back waveguides (second and third loop-back waveguide structure 1204a/b and 1206a/b).

Self-Alignment Structures

[0186] In some embodiments, the first and second substrates of IOCS device may comprise self-alignment structures configured to facilitate the alignment between the substrates during fabrication of the IOCS.

[0187] In some embodiments, a self-alignment structure may comprise portions on both substrates configured to be mechanically engaged and to align the two substrates upon engagement. The self-alignment structures may have a male-female relationship. In some embodiments, a first alignment structure on the first substrate may comprise a male component, e.g., a plurality of pins, protrusions, posts, segments, tabs or other forms of protrusions and a second alignment structure on the second substrate may comprise a female component, e.g., a plurality of holes, openings, grooves, indentations, vias, trenches, slots or other forms of recesses configured to receive the respective male component. In some implementations, the shapes and dimensions of a pair of self-alignment structures on the two substrates may be configured to be coupled and and/or to be engaged within a predetermined tolerance that is suitable for optical coupling of various components as described herein. For example, the female component may have an opening width that is larger than the male component by an amount that corresponds to a tolerance specification for the various optical coupling structures described above.

[0188] In some embodiments, both the first and second alignment structures can include female components or recesses that can be coupled by a third alignment structure that can be inserted into both the first and second alignment structures. For example, the first alignment structure on the first substrate may comprise a first plurality of recesses and a second

alignment structure on the second substrate may comprise a second plurality of recesses, where the first and second recesses are configured to be mechanically coupled to each other by a plurality of microbeads.

[0189] In some embodiments, the self-alignment structures may be formed on regions of major surface of a substrate different from region over which the layers and/or structures associated with the waveguides, optical switches, and inter-layer couplers, and optical ports are fabricated.

[0190] It will be appreciated that different shaped protrusions and recesses can be mixed and matched as part of the paired alignment structures. Figures 13A-13C schematically illustrate perspective views of three pairs of substrates (or wafers) having self-alignment structures comprising protrusions and recesses having different shapes. In the example shown in Figure 13A, the first substrate 602 comprises grooves such as elongate V-grooves 1304a/b and the second substrate 704 comprises rounded protrusions such as semispherical protrusions 1302 configured to be received and be engaged to the elongate V-grooves. In the example shown in Figure 13B, the first substrate 602 comprises four pyramidal openings 1306 and the second substrate 704 comprises four semispherical protrusions 1302 configured to be received and be engaged to the three pyramidal openings. In the example shown in Figure 13C, the first substrate 602 comprises three elongate V-grooves 1304a/b and the second substrate 704 comprises three rectangular protrusions 1308 configured to be received and be engaged to the three elongate V-grooves. In some implementations, a first group V-grooves can be elongated along a first direction and a second group of V-grooves can be elongated along a second direction. The first direction can be substantially perpendicular to the second direction. Such relative orientation of V-grooves may facilitate aligning the structures (e.g., shunt waveguide s with respect to the second plurality of bus optical waveguide) in two dimensions (e.g., along x-axis and y-axis). In the examples shown in Figures 13A-13C, a first elongated V-groove 1304a formed on the first substrate 602 is extended along a first direction and second and third V—grooves 1304b are extended along a second direction substantially perpendicular to the first direction.

[0191] Figures 13D-13F schematically illustrate see-through top views of the three pairs of substrates shown in Figures 13A-13C respectively when the two substrates of each

pair are overlapped and the portions of the self-alignment structures on the first and second substrates 602, 704 are engaged causing the two substrates to become at least partially aligned.

[0192] Figure 13G schematically illustrates a side close-up cross-sectional view of the first or third pairs of substrates (shown in Figures 13A and 13C) near an alignment structure when the two substrates of each pair are overlapped and the portions of the self-alignment structures on the first and second substrates 602, 704 are engaged. Figure 13H schematically illustrates a side close-up cross-sectional view of the second pairs of substrates (shown in Figure 13B) near an alignment structure when the two substrates of each pair are overlapped and the portions of the self-alignment structures on the first and second substrates 602, 704 are engaged.

[0193] As illustrated in Figures 13G and 13H, the paired alignment structures having different shapes (e.g., hemispherical and V grooves) as shown can be utilized to maintain a gap between the bonded substrates. In some embodiments, the first or second substrate may further comprise one or more spacers or stoppers 1310 configured to maintain a predetermine vertical spacing between the first and the second substrates 602, 704.

[0194] Figures 14A-14C schematically illustrate perspective views of three pairs of substrates (or wafers) having first and second self-alignment structures each comprising openings (or holes) having different shapes, where the openings on the first substrate 602 are configured to be mechanically coupled to the openings on the second substrate 704 by third self-alignment structure, e.g., microbeads 1402 (e.g., spherical microbeads). In the example shown in Figure 14A, the first substrate 602 comprises three elongate V-grooves 1304a/b and the second substrate 704 comprises three pyramidal openings 1306. In the example shown in Figure 14B, each of the first and second substrates 602, 704 comprises three pyramidal openings 1306. In the example shown in Figure 14C, each of the first and second substrates 602, 704 comprises four pyramidal openings 1306.

[0195] Figures 14D-14F schematically illustrate see-through top views of the three pairs of substrates shown in Figures 14A-14C, respectively, when the two substrates of each pair overlap and the portions of the self-alignment structures on the first and second substrates 602, 704 are and mechanically coupled by the three microbeads 1402 causing the two substrates to become at least partially aligned.

[0196] Figure 14G schematically illustrates a side close-up cross-sectional view of the three pairs of substrates (shown in Figures 14A-14C) near an alignment structure when the two substrates of each pair overlap and the portions of the self-alignment structures on the first and second substrates 602, 704 are mechanically coupled by a microbead 1402.

[0197] Figure 15A schematically illustrates a perspective view of a pair of substrates (or wafers) having self-alignment structures comprising cylindrical protrusions and holes. In the example shown in Figure 15A, the first substrate 602 comprises four cylindrical holes 1504 and the second substrate 704 comprises four cylindrical protrusions 1502 configured to be received and inserted into the four cylindrical holes 1504.

[0198] Figure 15B schematically illustrates a see-through top view of the pairs of substrates shown in Figure 15A when the two substrates overlap and the self-alignment structures on the first and second substrates 602, 704 are engaged, thereby causing the two substrates to become at least partially aligned.

[0199] Figure 15C schematically illustrates a side close-up cross-sectional view of the pair of substrates shown in Figure 15A near a pair of alignment structures on the first and second substrates 602, 704 when the two substrates overlap, and the alignment structures are engaged (the cylindrical pin is inserted into the cylindrical hole).

[0200] Figure 16A schematically illustrates a perspective view of a pair of substrates (or wafers) having self-alignment structures comprising rectangular posts or protrusions (or protrusions) 1602 and matching rectangular holes (or openings) 1604. In the example shown in Figure 16A the first substrate 602 comprises four rectangular holes 1604 and the second substrate 704 comprises four rectangular posts or protrusions 1602 configured to be received and inserted to the four rectangular holes 1604.

[0201] Figure 16B schematically illustrates a see-through top view of the pairs of substrates shown in Figure 16A when the two substrates are overlapped and the matched pairs of self-alignment structures on the first and second substrates 602, 704 are engaged causing the two substrates to become at least partially aligned.

[0202] Figure 16C schematically illustrates a side close-up cross-sectional view of the pair of substrates shown in Figure 16A near a pair of alignment structures on the first and second substrates 602, 704 when the two substrates overlap, and the alignment structures are engaged (the cuboidal protrusion is inserted into the cuboidal hole).

[0203] In some embodiments, the self-alignment structures described above with respect to Figures 13A-13F, 14A-14F, 15A-15C, 16A-16C may be formed on two regions of major surface of each substrate around or on the opposite sides of a region 1300 over which the layers and/or the waveguides, optical switches, and inter-layer couplers, optical ports, and related structures (e.g., anchors) are fabricated.

[0204] In various embodiments, the pins (or protrusions) 1302, 1502, 1602, and the openings (or holes) 1304a/b, 1504, 1604, may be formed on a substrate using photolithography and/or etching. For example, a polymer or photoresist layer may be disposed on a top layer of the substrate and the protrusions may be fabricated by photolithographic patterning, etching (e.g., wet or dry etching), or a combination thereof or other known methods.

[0205] In some embodiments, the pins (or protrusions) 1302, 1502, 1602 may be directly deposited on or attached to substrate as preformed structures.

[0206] In various embodiments, the pins (or protrusion) 1302, 1308, 1502 and the microbeads may comprise a photoresist, a polymer, a metal, a glass, a ceramic, a silicon, or other materials.

[0207] In some implementations, the width of a V-groove 1304a/b can be from 100 to 1000 microns and the depth of the V-groove 1304a/b can be from 5 to 500 microns.

[0208] In some implementations, the width of a pyramidal opening can be from 100 to 1000 microns and the depth of the pyramidal opening can be from 5 to 500 microns.

[0209] In some implementations, the diameter of a cylindrical hole 1504 can be from 10 to 1000 microns and the depth of the cylindrical hole 1504 can be from 5 to 500 microns.

[0210] In some implementations, the diameter of a spherical microbead 1402 can be from 10 to 1000 microns and the diameter of semispherical protrusion 1302 can be from 10 to 1000 microns.

[0211] In some embodiments, the active alignment structures and/or self-alignment structures described above with respect to Figures 12A-12C, and Figures 13A-13F, 14A-14F, 15A-15C, 16A-16C, may be generally used for aligning two wafers or two substrates each comprising an integrated photonic circuit or a portion of an integrated photonic circuit. In some implementations, the active alignment structures and/or self-alignment structures may be used to optical devices and/or optical device portions fabricated on different substrates or wafers of

a pair of substrates or wafers. In some implementations, these optical devices and/or optical device portions may not have any movable region. In some implementations, these optical devices and/or optical device portions may not include a MEMS actuator. In some implementations, the active alignment structures and/or self-alignment structures may be used to evanescently couple optical devices and/or optical device portions fabricated on different substrates or wafers of a pair of substrates or wafers.

[0212] In various embodiments, the actuators used in the optical switches of the IOCS devices described above may comprise piezoelectric MEMS actuators.

Integrated Optical Circuit Switch with sensors

[0213] In some embodiments, an IOCS, e.g., any of the IOCS devices described above or different types of IOCS, may include one or more monitor sensors configured to generate sensor signals usable for determining an ON/OFF state of an optical switch in the IOCS and/or an amount of light rerouted by the optical switch. In some embodiments, a monitor sensor may be configured to detect a mechanical displacement of a shunt waveguide of an optical switch. In some examples, a monitor sensor can be an electrical or electro-mechanical sensor (e.g., a capacitive sensor with a moving plate) used to detect a displacement of one or both ends of the shunt waveguide and generate a sensor signal indicative of the magnitude of the displacement. In some examples, a monitor sensor can be a photodetector configured to receive light from an optical waveguide (e.g., a bus optical waveguide or a recovery optical waveguide of the IOCS) that receives light via an optical switch. In various embodiments, a monitor sensor can be a silicon based, germanium-based photodetector, or a photodetector based on III-V semiconductor material(s). In some embodiments, a monitor sensor can be p-i-n photodiode based any of the above materials (e.g., a germanium p-i-n photodiode). In some examples, the intrinsic region of the p-i-n photodiode used to measure or monitor optical power propagating in a bus optical waveguide may comprise a portion of the bus optical waveguide. In some such examples, one or more sensor signals (e.g., a photocurrents) generated by the one or more photodetectors may indicate an amount of light rerouted by the optical switch to the optical waveguide and can be used to determine whether the corresponding optical switch is in ON or OFF state and/or determine an efficiency of the optical switch for rerouting optical power (e.g.,

a ratio between optical power received by the optical switch and optical power re-routed to another bus optical waveguide).

[0214] In various embodiments, a monitor sensor can be integrated with the IOCS on a common substrate. In some embodiments, at least a portion of a monitor sensor may comprise a portion of an optical switch or an optical waveguide. In some embodiments, at least a portion of a monitor sensor may be bonded to the IOCS (e.g., to a substrate or a waveguide layer of the IOCS). In some embodiments, at least a portion of the monitor sensor may be fabricated with an optical switch or a bus optical waveguide on or over a common substrate.

[0215] In some embodiments, a monitor sensor can be electrically linked to an electronic circuit (e.g., an electronic control and/or processing circuit) configured to receive a sensor signal and determine an ON/OFF state or an efficiency of an optical switch based at least in part on the sensor signal. In some cases, the determined state of the optical switch based on one or more sensor signals may be referred to as a measured state of the optical switch. In some embodiments, the electronic circuit may further receive a signal associated with an activation signal provided to an optical switch to determine an intended state of the optical switch and then compare the intended state of the optical switch with the measured state of the optical switch to determine a functionality of the optical switch. For example, when the electronic circuit detects a discrepancy between the intended and measured states of an optical switch it may determine that the optical switch is malfunctioning. In some embodiments, the electronic circuit may use one or more sensor signals to determine the efficiency of an optical switch, compare the determined efficiency with a threshold value (e.g., a minimum desired efficiency), and if the determined efficiency is less than a desired value, generate a signal indicating a malfunctioning or defective optical switch. In some embodiments, when the electronic circuit determines that an optical switch is malfunctioning (or defective), the electronic circuit may generate an alert signal indicative of an error and/or a position of a defective optical switch causing the error (e.g., with respect to columns and rows in an optical switch matrix). In some embodiments, the alert signal may be provided to user and/or used to address the error, e.g., by modifying (e.g., increasing) an activation signal provided to the identified defective (or malfunctioning) optical switch, rerouting optical signals to other bus optical waveguides to avoid the optical routes controlled by the defective switch. In some cases, when an IOCS is being tested in a factory, such alert signals may be used to detect defective

switches and determine a pass or fail assessment for the IOCS and in some cases, the wafer comprising the IOCS. In some embodiments, the alert signal may be provided to the user via a user interface in communication with the electronic circuit. In various embodiments, the electronic circuit can be connected to the optical switches and/or monitor sensors via wired or wireless links. In some cases, the electronic circuit may be integrated with the IOCS on a common chip, mounted on a common carrier chip with the IOCS, or otherwise positioned in a same enclosure or package with the IOCS. In some embodiments, the electronic circuit and IOCS may form an optical system for rerouting optical signals the optical system capable of monitoring the performance of the optical switches on the IOCS and, in some embodiments, recover the functionality of the IOCS when an optical switch fails, malfunctions.

[0216] Figure 17A schematically illustrates a top view of an IOCS comprising monitor photodetectors (mPDs) configured to receive a portion of light propagating in the first and second pluralities of the bus optical waveguide 102, 104 formed over a substrate (e.g., in the same or different waveguide layers). In some implementations, the first and second pluralities of bus optical waveguide may be terminated by a first and second pluralities of optical ports 106, 112, formed over the substrate (e.g., in the same or different waveguide layers). In the example shown, some of the mPDs are directly coupled to the bus optical waveguides to an output facet of the bus optical waveguides and some of the mPDs are coupled to the bus optical waveguides by optical tap couplers (also referred to as tap couplers). In some cases, a tap coupler may comprise a waveguide section evanescently coupled to an optical waveguide to reroute a portion of light propagating in the optical waveguide to a mPD. The mPD may generate a sensor signal indicative of the power of light received via the tap coupler and thereby the total power of light propagating in the optical waveguide. In various implementations, the portion of light coupled out of a waveguide by the tap coupler can be from 0.1% to 1%, from 1% to 3%, from 3% to 5%, from 5% to 8%, from 8% to 10 % or any ranges formed by these values or larger or smaller values.

[0217] With continued reference to Figure 17A, IOCS device 1701 comprises a first plurality of mPDs 1704a configured to receive portions of light propagating in the first plurality of bus optical waveguides 102 (e.g., toward the first plurality optical ports 106), through a first plurality of tap couplers optically coupled (e.g., evanescently coupled) to the first plurality of bus optical waveguides 102. In some examples, the first plurality of tap

couplers can be optically coupled to the first plurality of bus optical waveguides 102 at positions between a first plurality of optical ports 106 ("A₁", ..., "A_m"), and the respective optical switches configured to reroute light between the first plurality of bus optical waveguides 102 and the respective ones of the second plurality of bus optical waveguides 104.

[0218] IOCS device 1701 may further comprise a second plurality of mPDs 1704b configured to receive portions of light propagating in the second plurality of bus optical waveguides 104 (e.g., toward the second plurality optical ports 112), through a second plurality of tap couplers optically coupled (e.g., evanescently coupled) to the second plurality of bus optical waveguides 104. In some examples, the second plurality of tap couplers can be optically coupled to the second plurality of bus optical waveguides 104 at positions between the second plurality optical ports 112 ("B₁", ..., "B_n"), and the respective optical switches configured to reroute light between the first plurality of bus optical waveguides 102 and the respective ones of the second plurality of bus optical waveguides 104. In some cases, each tap coupler of the first plurality of tap couplers may couple between 1% to 5% of light propagating in a respective bus optical waveguide of the first and second pluralities of bus optical waveguides 102, 104, to an mPD coupled to an end of tap coupler opposite another end coupled to the bus optical waveguide.

[0219] In some embodiments, the first and second pluralities of the mPDs 1704a, 1704b, can be electrically coupled to an electronic circuit 1708 to provide a first and second pluralities of sensor signals (mPDs A₁, ..., A_m and mPDs B₁, ..., B_m), also referred to as detector signals, generated by the first and second pluralities of the mPDs 1704a, 1704b, respectively, to the electronic circuit 1708. In some embodiments, the electronic circuit 1708 may process the first and second pluralities of detector signals (mPDs A₁, ..., A_m and mPDs B₁, ..., B_m) to detect and locate a failed or defective optical switch of the IOCS device 1701. In some embodiments, the electronic circuit 1708 may additionally receive indications of activation signals being provided to the optical switches of the IOCS device 1701 and use these signals to detect and locate failed optical switches. In some embodiments, an activation signal is an electric signal provided to a MEMS actuator of an optical switch to movably couple the shunt waveguide of the optical switch to one or more bus optical waveguides. In some embodiments, an indication of an activation signal being provided to an optical switch may comprise a portion of the actuation signal or an indicator signal (e.g., a digital signal) whose amplitude or phase

indicates that the activation signal is (or was) provided to an optical switch. In some examples, the indicator signal or port from which the indicator signal is received may comprise the location of the optical switch with respect to the optical switch matrix and/or the bus optical waveguides of the IOCS device 1701. For example, an electronic circuit 1708 may receive a signal indicating an activation signal is provided to a first optical switch to reroute light received from a first port or the first plurality of optical ports 106 from a first bus optical waveguide of the first plurality of bus optical waveguides 102 to a second bus optical waveguide of the second plurality of bus optical waveguides 104. Further, the electronic circuit 1708 may receive a first sensor signal from a first mPD of the second plurality of mPDs 1704a indicating an amount of light (e.g., power of light) coupled from the first bus optical waveguide to the second bus optical waveguide and in response to determining that the first sensor signal is below a signal threshold value (indicating that the optical power rerouted by the optical switch is lower than a power threshold value), the electronic circuit 1708 may generate an alert signal.

[0220] In some embodiments, an IOCS device may comprise mPDs configured to receive and monitor light output by output optical ports and/or mPDs located at end regions of the bus optical waveguides configured to receive and monitor light provided through the optical port of the same bus optical waveguide.

[0221] Figure 17B schematically illustrates a top view of another example IOCS device 1702 comprising a plurality of mPDs for monitoring light propagating in a plurality of bus optical waveguides. In various embodiments, the IOCS device 1702 may comprise one or more features described above with respect to IOCS device 1701. Similar the IOCS device 1701, IOCS device 1702 comprises first and second pluralities of bus optical waveguides 102, 104, terminated at first and second pluralities of optical ports 106, 112, a plurality of optical switches to controllably optically couple individual ones of the first plurality of waveguides 102, to the individual ones of the second plurality of waveguides 104, and first and second pluralities of mPDs 1704a, 1704b, coupled to the first and second pluralities of bus optical waveguides 104, 102 at positions between the first and second pluralities of optical ports 106, 112 and the respective optical switches. As described above, the first and second pluralities of mPDs 1704a, 1704b, can detect portions of light coupled from the first plurality of bus optical waveguides to the second plurality of bus optical waveguides, and vice versa. In some

embodiments, in addition to first and second pluralities of mPDs 1704a, 1704b, IOCS device 1702 can include mPDs configured to monitor optical power passed through (not re-routed by) the optical switches. For example, IOCS device 1702, can include a third plurality of mPDs 1706a configured to receive light from end regions (e.g., waveguide ends) of the first plurality of bus optical waveguides 102 and a fourth plurality of mPDs 1706b configured to receive light from end regions (e.g., waveguide ends) of the second plurality of bus optical waveguides 104. For example, an mPD of the third plurality of mPDs 1916 may be butt coupled to a bus optical waveguide of the first plurality of bus optical waveguides 102 terminating at an optical port of the first plurality of optical ports 106, via an end region of the bus optical waveguide opposite to the optical port. The mPD may receive a portion of light input to the bus optical waveguide (via the optical port) and directly transmitted to the mPD without being coupled or re-routed to a waveguide of the second plurality of bus optical waveguides 104. In some implementations, the first, second, third and fourth pluralities mPDs 1704a, 1704b, 1706a and 1706b, can be electrically connected the electronic circuit 1708 configured to receive first, second, third, and fourth detector signals (mPD A1..Am, mPD B1..Bm, mPD C1..Cm, mPD D1..Dm,) from the first, second, third and fourth pluralities mPDs 1704a, 1704b, 1706a and 1706b, and use the first, second, third, and fourth detector signals to determine states or functionality of the optical switches of the IOCS device 1702. For example, a first detector signal received from a mPD of the first plurality of mPDs 1704a may indicate an amount of light re-routed by an optical switch and a fourth detector signal received from a mPD of the fourth plurality of mPDs 1706b may indicate an amount of light that is not re-routed) by the optical switch. In some embodiments, the electronic circuit 1708 may use one or both first and second pluralities of detector signals to determine an ON/OFF state of the optical switch. Moreover, in some embodiments, the electronic circuit may use both first and second signals to determine a ratio of light coupled by the optical switch and transmitted through the optical switch (not coupled). In some such embodiments, determining such ratio may allow the electronic circuit 1708 to determine a modification to an activation signal to increase the ratio above a threshold level. Advantageously, monitoring an amount of light coupled by an optical switch and amount of light passing through an optical switch (light not coupled to the optical switch and/or rerouted by the optical switch), may be used to determine efficiency of the optical

switch and/or displacement of the shunt waveguide of an optical switch (e.g., vertical displacements of the coupling ends) with respect to the respective bus optical waveguides.

[0222] Figure 17C schematically illustrates a top view of another example IOCS device 1703 comprising a plurality of inline mPDs for monitoring light propagating in a plurality of bus optical waveguides. In various embodiments, the IOCS device 1703 may comprise one or more features described above with respect to IOCS device 1702 and/or IOCS device 1703. Similar the IOCS devices 1701, 1702, IOCS device 1703 comprises a first and second pluralities of waveguides 102, 104, terminated at first and second pluralities of optical ports 106, 112, a plurality of optical switches to controllably optically couple individual ones of the first plurality of waveguides 102, to the individual ones of the second plurality of waveguides 104, and a pluralities of mPDs directly optically coupled to the first and second pluralities of bus optical waveguides 104, 102 at positions between the first and second pluralities of optical ports 106, 112 and the respective optical switches. In some embodiments, the pluralities of mPDs of the IOCS device 1703 comprise first and second pluralities of inline mPDs 1710a, 1710b, monolithically integrated with the first and second pluralities of the bus optical waveguides 102, 104, respectively. In some such embodiments, an inline mPD of the first and second plurality of inline mPDs 1710a, 1710b, may comprise a portion of a bus optical waveguide to which it is optically coupled to receive light. In some implementations, the individual mPD may be disposed near an end of the bus optical waveguide closer to an optical port. In some embodiments, an inline mPD of the first and second pluralities of inline mPDs 1710a, 1710b, may comprise a reverse biased photodiode (e.g., a reverse biased p-i-n photodiode). In some examples, where the inline mPD comprises a p-i-n photodiode, the intrinsic region of the individual mPD may comprise a region (e.g., an end region closer to an optical port) of the bus optical waveguide to which the inline mPDs is optically coupled to receive light. When reversed bias is applied to the p and n regions, free-carriers (electrons and holes) generated from the light in the bus optical waveguide can be swept to the p and n regions, resulting in a current change through the p-i-n diode proportional to the optical power propagating in the bus optical waveguide. In some embodiments, propagation of light in an inline mPD may generate electron-hole pairs via two-photon absorption (e.g., two-photon absorption in silicon) or defect/interface states assisted absorption. In some cases, these

photogenerated electron-hole pairs (free carriers) can move by a reverse-biased p-n junction to generate a photocurrent.

[0223] In some embodiments, similar to IOCS device 1702, in addition to first and second pluralities of mPDs 1710a, 1710b, IOCS device 1703 can include mPDs configured to monitor optical power passed through the optical switches (not redirect by the optical switches). These additional mPDs may comprise one or more features described above with respect to third and fourth pluralities of mPDs 1706a, 1706b, e.g., they may be configured to receive light from end waveguide regions of first and second pluralities of bus optical waveguides 102, 104 opposite to the first and second pluralities of optical ports 106, 112, respectively. In some implementations, these additional mPDs may be butt coupled to end regions of bus optical waveguides opposite to the optical ports or may be monolithically integrated with the end regions such that an individual mPD comprises the end region of a bus optical waveguide, to which is optically coupled, opposite to the optical port optically connected to the bus optical waveguide (similar to the first and second pluralities of mPDs 1706a, 1706b).

[0224] In some embodiments, one or more of the mPDs used to monitor an IOCS device can be external photodetectors that receive light from bus optical waveguides via an optical port or a waveguide facet. In some such embodiments, these external mPDs can be mounted, bonded, or otherwise integrated on a carrier chip along with IOCS device.

[0225] As described above, in some embodiments, an IOCS device may include an electrical or electro-mechanical sensor configured to directly monitor an optical switch. In some examples, the electrical or electro-mechanical sensor may be used for generating a sensor signal indicative of a displacement of a shunt optical waveguide (e.g., an end region of the shunt optical waveguide) with respect to a bus optical waveguide to which the optical switch is controllable optically coupled. In some implementations, the electrical or electro-mechanical sensor may comprise a capacitive sensor having at least one movable conductive plate mechanically coupled to the shunt optical waveguide (e.g., via a structure supporting the shunt optical waveguide). In some such implementations, the electro-mechanical sensor may be integrated with the optical waveguide. In some implementations, at least a portion of the electro-mechanical sensor may be co-fabricated with a bus optical waveguide or an optical switch. In some examples, capacitive sensor may comprise a fixed conductive plate formed on

a substrate or waveguide layer on or within which the bus optical waveguide is formed, and a movable conductive plate formed on a structure that mechanically supports a movable region of the shunt optical waveguide. In some examples, one or both the fixed and movable conductive plates may comprise a portion of the electro-mechanical actuator configured to move an end region of the shunt optical waveguide. For example, the same conductive plates that insert electro-mechanical force on one or both ends of a shunt waveguide may be used to detect and measure the movement and displacement of the shunt optical waveguide. In some embodiments, a capacitive sensor integrated with an optical switch may comprise a pair of capacitors, mechanically coupled to one of the end regions of the corresponding shunt optical waveguide. In some such embodiments, the capacitance of each capacitor of the pair of capacitors may indicate the mechanical displacement of one of the two end regions of the shunt optical waveguide with respect to a bus optical waveguide. Such capacitive sensor may be used to generate two sensor signals each indicative of the mechanical displacement of one of the end regions.

[0226] Figure 18 schematically illustrates a top view of an example IOCS device 1800 comprising optical switches having integrated capacitive sensors 1804 where individual capacitive sensors (not shown) are used to monitor a state (e.g., an ON/OFF state) of the individual optical switches. For example, a capacitive sensor may be electrically connected to an electronic circuit that uses the capacitive sensor to generate a sensor signal indicative of displacement of the respective shunt optical waveguide. In some examples, the electronic circuit may measure capacitance of the capacitive sensor and generate a sensor signal proportional to the measured capacitance. In some examples, the electronic circuit may comprise one or more features described above with respect to the electronic circuit 1708 described above with respect to IOCS device 1701. For example, the electronic circuit (not shown) may use the capacitive sensor to generate a plurality of sensor signals indicative of the states (e.g., ON/OFF states) and/or performance of the optical switches of the IOCS device 1703. In some embodiments, the IOCS device 1800 may comprise one or more features described above with respect to the IOCS device 200 (Figure 2A).

[0227] In some cases, a coupling gap (e.g., a vertical distance) between a shunt optical waveguide of an optical switch and a corresponding bus optical waveguide can be smaller than a threshold value in an ON state, and larger than the threshold value in an OFF

state. The electronic circuit may use a capacitive sensor integrated with the optical switch to measure the magnitude of the coupling gap and compared the measured magnitude of the coupling gap with a threshold value to determine a measured state of the shunt optical waveguide. In some cases, in response to detecting a discrepancy between the measured state of the shunt optical waveguide and an expected state of the shunt optical waveguide (e.g., based on presence or absence of an indication of an activation signal provided to the optical switch), the electronic circuit may determine that optical switch has failed.

[0228] As described above, in some embodiments, a pair of photodetectors or a capacitive sensor may generate or may be used to generate sensor signals indicative of a ratio between an amount of light re-routed by an optical switch and amount of light received by the optical switch from a bus optical waveguide. In some examples, such ratio may be referred to as efficiency of the optical switch. In some examples, a first photodetector of the pair of photodetectors may generate a first sensor signal indicative of an amount of light re-routed by the optical switch and the second photodetector may generate a second sensor signal indicative of an amount of light passed through the optical switch or the corresponding switching cell (not re-routed), and an electronic circuit (e.g., the electronic circuit 1708) may determine the efficiency of the optical switch by electronically processing the first and second sensor signals. In some examples, an electronic circuit may use the capacitive sensor to determine the efficiency of the optical switch based at least in part on a capacitance of the capacitive sensor and a pre-determined relation between the capacitance and optical switch efficiency.

[0229] As such, in some cases, a sensor signal generated using a capacitive sensor or sensor signals generated by a pair of photodetectors or a capacitive sensor may be used by an electronic circuit to determine an ON/OFF state of the corresponding optical switch by determining whether the efficiency of the optical switch is above or below a threshold value associated with the ON/OFF state. In some cases, in response to determining that efficiency of an optical switch is below the threshold value or above the threshold value but below a desired value, the electronic circuit may change an actuation signal provided to the optical switch to improve the efficiency of the optical switch or change the state of the switch.

[0230] In some embodiments, mPDs of an IOCS may monitor the output power at a plurality of optical ports, and the electronic circuit may compare the detected output power level with a desired output power level and in response to detecting a difference larger than the

tolerance threshold, between the detected and desired output power level, determine that an optical switch has failed.

[0231] In some embodiments, a pair of photodetectors or a capacitive sensor may generate or may be used to generate sensor signals indicative of a location of a failed optical switch in a network of optical switches. For example, a first photodetector of the pair of photodetectors may generate a first sensor signal indicative of an amount of light re-routed by the failed optical switch and the second photodetector may generate a second sensor signal indicative of an amount of light passed through the failed optical switch or the corresponding switching cell (not re-routed), and an electronic circuit (e.g., the electronic circuit 1708) may use the first and second sensor signals to determine the location of a failed optical switch with respect to waveguide-crossing junctions of the network of optical switches. In some examples, a capacitive sensor may be identified by the electronic circuit based on an electric port of the electronic circuit through which the capacitive sensor is connected to the electronic circuit. In such examples, the electronic circuit can determine the location of a failed optical switch with respect to waveguide-crossing junctions of the network of optical switches by identifying the capacitive sensor integrated with the optical switch.

[0232] In some embodiments, when input light is provided to a bus optical waveguide through an optical port, and none of the optical switches along the bus optical waveguide is in an ON state, an amount of optical power received by an mPD disposed at an end region of the bus optical waveguide (e.g., butt coupled to the waveguide) can be larger than 90%, larger than 95%, larger than 98%, or larger than 99% of the power of input light coupled to the bus optical waveguide. When one of the optical switches along the bus optical waveguide is turned ON, an amount of optical power received by an mPD disposed at the end region of the bus optical waveguide can be larger than 70%, smaller than 60%, smaller than 50%, smaller than 30%, smaller than 10%, smaller than 5% of the power of input light coupled to the bus optical waveguide. In some embodiments, when an actuation signal is provided to at least one optical switch along the bus optical waveguide (e.g., a voltage is applied to a MEMS actuator of the optical switch), to put the at least one optical switch in ON state and a sensor signal generated by the mPD at the end of the bus optical waveguide indicates an optical power level larger than 90% of the power of input light coupled to the bus optical waveguide, an electronic circuit may receive an indication of the actuation signal provided to the at least one optical switch.

optical switch and the sensor signal generated by the mPD to determine that at least one optical switch has failed or is malfunctioning because it is in an OFF state after receiving an actuation signal.

[0233] In some embodiments, when no actuation signal is provided to any of the optical switches along the bus optical waveguide (e.g., a voltage is applied to a MEMS actuators of the optical switch), to put the at least optical switch in ON state and a sensor signal generated by the mPD at the end of the bus optical waveguide indicates an optical power level larger less than 70% of the power of input light coupled to the bus optical waveguide, an electronic circuit may receive the sensor signal generated by the mPD and in the absence of an indication of an actuation signal provided to one of the optical switches along the bus optical waveguide, it may determine that at least one optical switch has failed or is malfunctioning because it is in an ON state without receiving an actuation signal.

[0234] In various embodiments, without receiving sensor signals from mPDs configured to receive light re-routed (or coupled) by the optical switches along the bus optical waveguide, a user or the electronic circuit may not be able to determine which optical switch of the plurality of optical switches along the bus optical waveguide has been failed or is malfunctioning. Advantageously, in embodiments where the IOCS includes mPDs configured to receive light re-routed (or coupled) by the optical switches and light passed through the optical switches (e.g., the IOCS device 1702), the user or the electronic circuit can determine the location of a failed optical switch with respect to waveguide-crossing junctions of the network of optical switches.

[0235] In various applications, the sensor configurations described above with respect to the IOCS devices 1701, 1702, and 1703 may integrated with the optical waveguides and optical switches of IOCS devices comprising a single waveguide layer formed on a single wafer, two waveguide layers formed on a single wafer, a waveguide layer formed on a wafer and a waveguide layer suspended over the wafer, two bonded wafers each including one waveguide layer of a pair of waveguide layers separated by a gap. For example, the sensor configurations described above with respect to the IOCS devices 1701, 1702, and 1703 may be integrated with IOCS devices 200, 201, 600, or 700. In some cases, these sensor configurations may be in communication with an electronic circuit (e.g., electronic processing circuit) configured to monitor the optical switches based on an of the methods described above.

Additionally, in some cases, the electronic circuit may control one or more actuation signals provided to the optical switches based at least in part on the one or more sensor signals received from one or more sensors of the sensor configuration.

[0236] In some embodiments, an IOCS (e.g., a chip or substrate comprising the IOCS) may be integrated, mounted, bonded, or otherwise electrically connected to a chip comprising an electronic circuit (e.g., integrated circuit, IC) configured to monitor and/or drive the optical switches of the IOCS. In some examples, the electronic circuit may comprise a CMOS circuit 1802 (e.g., a CMOS circuit fabricated on a wafer or chip separate from the IOCS 1800). In the example shown in Figure 18, the IOCS device 1800 is integrated with a CMOS circuit 1802 that is electrically connected to the capacitive sensors of the IOCS device 1800 and is configured to monitor states of the optical switches therein using the capacitive sensors. In some examples, the CMOS circuit 1802 may be further configured to control the states of the optical switches. In some examples, the actuators of the optical switches may comprise the capacitive sensors (e.g., the actuating conductive plates may serve as conductive plates of the capacitor). In some embodiments, IOCS 1800 may be electrically connected and bonded to the CMOS circuit 1802 by a plurality of solder balls. In some examples, CMOS circuit 1802 may comprise, application-specific integrated circuit (ASIC), field programmable gate array (FPGA).

IOCS devices with recovery optical waveguides

[0237] In some embodiments, an IOCS may include recovery optical switches and recovery optical waveguides configured for establishing recovery optical paths when one or more optical switches of the IOCS fails. In some such embodiments, in response to determining that an optical switch is malfunctioning, has failed, or is defective, an electronic circuit may establish a recovery optical path that bypasses or avoids the failed optical switch to maintain or provide optical connectivity between two optical ports that were supposed to be optically connected by the failed optical switch. In some examples, the electronic switch may establish the recovery optical path via a recovery optical waveguide of the IOCS, by generating one or more recovery activation signals that activate one or more recovery optical switches configured to controllably optically couple the recovery optical waveguide to the bus optical waveguides connected to the two optical ports.

[0238] Figure 19A schematically illustrates a top view of two bus optical waveguides 102a, 104a of an IOCS device 1900 having a recovery optical waveguide 1902a and first and second recovery optical switches 1906a, 1905a for bypassing a primary optical switch 1904a. In some embodiments, the IOCS device 1900 may comprise a first bus optical waveguide 102a formed on or over a substrate (e.g., in a first waveguide layer formed on the substrate) and a second bus optical waveguide 104a formed over the substrate (in the first waveguide layer or a second waveguide layer vertically separated from the first waveguide layer) and a primary optical switch 1904a that can controllably optically couple the first and second optical waveguides 102a, 104a. In some embodiments, the first bus optical waveguide 102a may be extended from a first optical port 106a near a first edge of the IOCS device 1900 away from the first edge along a first direction (e.g., substantially parallel to the x-axis) and second bus optical waveguide may be extended from a second optical port 112a near a second edge of the IOCS device 1900 away from the second edge along a second direction (e.g., substantially parallel to the y-axis). In some cases, the first and second directions can be substantially perpendicular, however the embodiments are not so limited and an angle between the first and second directions can have any value.

[0239] In some examples, the primary optical switch 1904a may be activated by a first activation signal provided by an electronic circuit 1708. In some implementations the primary optical switch 1904a may comprise a first shunt optical waveguide configured to move from an OFF state with respect to the first and second optical waveguides 102a, 104a, to an ON state, upon being activated by the first activation signal. In the OFF state the first shunt optical waveguide is optically decoupled at least from one of the first and second bus optical waveguides, 102a, 104a, and in the ON state the first shunt optical waveguide optically couples the first bus optical waveguide 102a and the second bus optical waveguide 104a to redirect light from the first bus optical waveguide 102a to the second bus optical waveguide 104a, or vice versa.

[0240] In some embodiments, integrated optical circuit may include a recovery optical waveguide 1902a configured to establish a recovery optical path between the first and second bus optical waveguides 102a, 104a, e.g., when an optical path between the first and second bus optical waveguides cannot be established by the primary optical switch 1904a and through the first shunt optical waveguide therein. In some implementations, the recovery

optical waveguide 1902a can be controllably optically coupled to the first bus optical waveguide 102a by a first recovery optical switch 1905a and to the second bus optical waveguide 104a by a second recovery optical switch 1906a. In some implementations, the recovery optical waveguide 1902a may extend from a first end near the first bus optical waveguide 102a (e.g., between the first optical port 106a and the primary optical switch 1904a) to a second end near the second bus optical waveguide 104a (e.g., between the second optical port 112a and the primary optical switch 1904a). In some implementations, the recovery optical waveguide 1902a may extend from a first end near a first edge of the IOCS device 1900 to a second end near a second edge of the IOCS device 1900 crossing the first bus optical waveguide 102a at a first crossing region (e.g., between the first optical port 106a and the primary optical switch 1904a) and crossing the second bus optical waveguide 104a at a second crossing region (e.g., between the second optical port 112a and the primary optical switch 1904a). In some examples, the first and second edges may extend along two substantially perpendicular directions, however the embodiments are not so limited and other configurations are possible. In some embodiments, the recovery optical waveguide 1902a may comprise at least one curved region. In some cases, the first and second crossing regions may be configured to prevent cross coupling of light between the first or second bus optical waveguides 102a, 104a, and the recovery optical waveguide 1902a.

[0241] In some implementations, the first recovery optical switch 1904a may comprise a second shunt optical waveguide configured to move from an OFF state with respect to the first bus optical waveguide 102a and the recovery optical waveguide 1902a, to an ON state, upon being activated by a second activation signal received from electronic circuit 1708. In the OFF state the second shunt optical waveguide is optically decoupled at least from one of the first bus optical waveguide, 102a and the recovery optical waveguide 1902a, and in the ON state the second shunt optical waveguide optically couples the first bus optical waveguide 102a and the recovery optical waveguide 1902a to redirect light from the first bus optical waveguide 102a to the recovery optical waveguide 1902a, or vice versa. In some embodiments, the first recovery optical switch 1905a may be formed between the first optical port 106a and the primary optical switch 1904a, where the first bus optical waveguide 102a and the recovery optical waveguide 1902a are close or cross each other, such that the second shunt optical

waveguide can be configured to couple the first bus optical waveguide 102a to the recovery optical waveguide 1902a.

[0242] In some implementations, the second recovery optical switch 1906a may comprise a third shunt optical waveguide configured to move from an OFF state with respect to the second bus optical waveguide 104a and the recovery optical waveguide 1902a, upon being activated by a third activation signal received from electronic circuit 1708. In the OFF state the third shunt optical waveguide is optically decoupled at least from one of the second bus optical waveguide, 104a and the recovery optical waveguide 1902a, and in the ON state the third shunt optical waveguide optically couples the second bus optical waveguide 104a and the recovery optical waveguide 1902a to redirect light from the second bus optical waveguide 104a to the recovery optical waveguide 1902a, or vice versa. In some embodiments, the second optical switch 1906a may be formed between the second optical port 112a and the primary optical switch 1904a, where the second bus optical waveguide 102a and the recovery optical waveguide 1902a are close or cross each other, such that the third shunt optical waveguide can be configured to couple the second bus optical waveguide 104a to the recovery optical waveguide 1902a.

[0243] In various implementations, the electronic circuit 1708 may be configured to monitor the primary optical switch 1904a to determine an ON/OFF state of the primary optical switch 1904a. In some embodiments, the electronic circuit 1708 may receive at least a first sensor signal (detector signal) from a first monitor sensor configured to monitor an ON/OFF state of the primary optical switch 1904a. In various implementations, the monitor sensor may comprise a capacitive sensor integrated with the primary optical switch 1904a, or a photodetector optically coupled to one or both the first and second bus optical waveguides 102a, 104a. In various implementations, the first monitor sensor may comprise one or more features described above with respect to the IOCS devices 1701, 1702, 1703 and 1800 and can be integrated with the first and second bus optical waveguides 102a, 104a, and the primary optical switch 1904a, based on any of the configurations described above with respect to the IOCS devices 1701, 1702, 1703 and 1800.

[0244] For example, the first monitor sensor may comprise one or both of a first photodetector 1912a receiving light from an end of the first bus optical waveguide 102a opposite the first optical port 106a and a photodetector 1914a receiving light from an end of

the second bus optical waveguide 104a opposite the second optical port 112a. In various implementations, one or both the first and second photodetectors 1912a, 1914a may be fabricated, disposed, or bonded to the substrate on which the first and second bus optical waveguides 102a, 104a are fabricated; however, the embodiments are not so limited and in some cases one or both the first and second photodetectors 1912a, 1914a can be external photodetectors configured (e.g., optically aligned) to receive light from first and second bus optical waveguides 102a, 104a.

[0245] In some embodiments, the electronic circuit 1708 may control the ON/OFF state of the primary optical switch 1904a by generating the first activation signal (e.g., based on a control signal received from another electronic circuit). In some implementations, the electronic circuit 1708 may receive an indication of the first activation signal provided to the primary optical switch 1904a by another electronic circuit. In some embodiments, electronic circuit 1708 may be configured to determine an intended state of the ON/OFF switch, e.g., based on a signal received from another electronic circuit. In some examples, the signal can be the first activation signal, or a signal indicating that the first activation signal was provided to the primary optical switch 1904a.

[0246] In some embodiments, the electronic circuit 1708 may control the ON/OFF state of the first and second recovery optical switches 1905a, 1906a by generating the second and third activation signals. Additionally, in some implementations, the electronic circuit 1708 may be configured to monitor the first and second recovery optical switches 1905a, 1906a to determine an ON/OFF state of the first and second recovery optical switches 1905a, 1906a. In some embodiments, the electronic circuit 1708 may receive a second and third sensor signals from second and third monitor sensors configured to monitor an ON/OFF state of the first and second recovery optical switches 1905a, 1906a, respectively. In various implementations, the monitor sensor may comprise a capacitive sensor integrated with the primary optical switch 1904a, or a photodetector optically coupled to one or both the first and second bus optical waveguides 102a, 104a. In various implementations, the second and third monitor sensors may comprise one or more features described above with respect to the IOCS devices 1701, 1702, 1703 and 1800 and can be integrated with the first and second bus optical waveguides 102a, 104a, and the primary optical switch 1904a, based on any of the configurations described above with respect to the IOCS devices 1701, 1702, 1703 and 1800.

[0247] For example, the second and third monitor sensors may comprise third and fourth photodetectors 1916a, 1918a receiving light from the first and second end of the recovery optical waveguide 1902a, respectively. In various implementations, one or both the third and fourth photodetectors 1916a, 1918a, may be fabricated, disposed, or bonded to the substrate on which the first and second bus optical waveguides 102a, 104a are fabricated; however, the embodiments are not so limited and in some cases one or both the third and fourth photodetectors 1916a, 1918a can be external photodetectors configured (e.g., optically aligned) to receive light from the recovery optical waveguide 1902a.

[0248] In some embodiments, in response to receiving one or more sensor signals the electronic circuit 1708 may generate the second and third activation signals and provide them to the first and second recovery optical switches 1904a, 1906a, to activate the first and second recovery optical switches 1904a, 1906a and establish the recovery path between the first and second bus optical waveguides 102a, 104a. In some cases, the one or more sensor signals may be indicative of a malfunction of the primary optical switch 1904a. In some examples, the electronic circuit 1708 may include a processing circuit 1708a and a driver circuit 1708b. The processing circuit 1708a may receive the one or more sensor signals from one or more monitor sensors, process the sensor signals to determine that the first recovery optical switch 1905a is malfunctioning, and in response to such determination cause the driver circuit 1708b to generate the second and third activation signals and provide them to the first and second recovery optical switches 1904a, 1906a, to establish the recovery path. In various implementations, the driver circuit 1708b may provide the second and third activation signals to the first and second recovery optical switches 1904a, 1906a, substantially at the same time or at different times (e.g., sequentially).

[0249] In some examples, the electronic circuit 1708 may receive an indication of the first activation signal provided to the primary optical switch 1904a (e.g., by another electronic circuit) or otherwise determine an intended ON state of the primary optical 1904a, determine a current ON/OFF state based on the first sensor signal, associated with the primary optical switch 1904a, and in response to detecting a discrepancy between the intended and current state of the primary optical switch 1904a, activate the first and second recovery optical switches 1905a, 1906a to establish the recovery optical path.

[0250] In some embodiments, once the first and second recovery optical switches 1905a, 1906a are activated, the electronic circuit 1708 may use the second and third sensor signals, associated with the first and second recovery optical switches 1905a, 1906a, to determine that first and second recovery optical switches 1905a, 1906a are activated and the recovery optical path has been established via the recovery optical waveguide 1902a.

[0251] In various embodiments, the bus optical waveguides 102a, 104a and the primary optical switch 1904a can be bus optical waveguides of the first and second pluralities of bus optical waveguides 102, 104, and an optical switch of any of the IOCS devices 200, 201, 202, 203, 1701, 1702, 1703 or 1800 and the recovery optical waveguide 1902a and the first and second recovery optical switches 1906a, 1905a may be formed on any of these IOCS devices to establish a recovery optical path for bypassing the optical switch.

[0252] In various applications, the IOCS device 1900 may comprise a single waveguide layer formed on a single wafer, two waveguide layers formed on a single wafer, a waveguide layer formed on a wafer and a waveguide layer suspended over the wafer, two bonded wafers each including one waveguide layer of a pair of waveguide layers separated by a gap. In some embodiments, the first and second bus optical waveguides 102a, 104a, and the recovery optical waveguide 1902a may be formed in a single waveguide layer on a substrate. In some embodiments, the IOCS device 1900 may comprise one or more features described above with respect to IOCS device 600 or IOCS device 700. For example, the first optical waveguide 102a and a first section of the recovery optical waveguide 1902a may be formed in first waveguide layer and the second optical waveguide 104a and a second section of the recovery optical waveguide 1902a may be formed in a second waveguide layer vertically separated from the first waveguide layer.

[0253] In some embodiments, one or more of the photodetectors 1916a, 1912a, 1918a and 1918a can be external photodetectors that receive light from bus optical waveguides a waveguide facet near an edge of the IOCS device 1900. In some such embodiments, these external photodetectors can be mounted, bonded, or otherwise integrated on a carrier chip along with IOCS device.

[0254] Figure 19B schematically illustrates a top view of an example IOCS device 1901 having recovery optical waveguides formed in a single waveguide layer (e.g., a waveguide layer formed on a substrate) and recovery optical switches for establishing recovery

optical paths via the recovery optical waveguides. In some implementations, the IOCS device 1901 may include, a first plurality of bus optical waveguides 102 extended from a first plurality of optical ports 106 (A1,..., A_m) to a first plurality of mPDs 1912 (mPD A1,... mPD A_m) and a second plurality of bus optical waveguides 104 extended from a second plurality of optical ports 112 (B1,..., B_n) to a second plurality of mPDs 1914 (mPD B1,... mPD B_m), and a plurality of primary optical switches 1904 formed at crossing points of the bus optical waveguides and configured to controllably optically couple individual ones of the first plurality of bus optical waveguides 102 to individual ones of the second plurality of bus optical waveguides 104. In some cases, an individual port can be connected (e.g., optically connected) to a corresponding bus optical waveguide, and an individual mPD can be located at the end of an individual bus optical waveguide (e.g., the individual mPD can be butt coupled to the bus optical waveguide). The IOCS device 1901 may further include a plurality of recovery optical waveguides 1902 extended from a third plurality of mPDs 1916 (mPD C1,..., mPD C_m) to a fourth plurality of mPDs 1918 (mPD D1,..., mPD D_m). In some embodiments, one or more of the recovery optical waveguides 1902 may comprise a bent waveguide region (e.g., a 90-degree bending). In some embodiments the first and third pluralities of mPDs 1912, 1916, may be formed or disposed along a first edge of the IOCS device 1901 and the second and fourth pluralities of mPDs 1914, 1918, may be formed or disposed along a second edge of the of the IOCS 1902. In some examples, the first and second edges can be substantially perpendicular to each other, however the embodiments are not so limited and the angle between the first and second edges of the IOCS device 1901 can be an angle different from 90 degrees. The IOCS device 1901 may comprise first plurality of recovery optical switches configured to controllably optically couple the plurality of recovery optical waveguides 1902 to the first plurality of the bust optical waveguides 102 and a second plurality of recovery optical switches 1906 configured to controllably optically couple the plurality of recovery optical waveguides 1902 to the second plurality of the bust optical waveguides 104. In some examples, the plurality of primary of optical switches 1904 may form a primary optical switch array 1910 having m rows and n columns ($m \times n$ array), the first plurality of recovery optical switches 1905 may form a first recovery switch array (or matrix) 1909a having m rows and q columns ($m \times q$ array), and the second plurality of recovery optical switches 1906 may form a second recovery optical switch array 1909b having q rows and n columns ($q \times n$ array). In some cases, the first plurality

of optical waveguides 102 and the rows of optical switches may be extended along a first direction (e.g., x -axis) and the second plurality of optical waveguides 104 and the columns of optical switches may be extended along a second direction (e.g., y-axis). In some examples, the first and second directions may be substantially perpendicular to each other, however embodiments are not so limited and the angle between the first and second directions can be an angle different from 90 degrees. In some embodiments, an individual recovery optical waveguide may have m crossing points with the first plurality of bus optical waveguides 102 and n crossing points with the second plurality of bus optical waveguides 104 and a recovery optical switch can be formed at or near each of these crossing points, forming the first and second recovery optical switch arrays 1909a, 1909b. In some embodiments, recovery optical waveguides 1902 and bus optical waveguides, and the first and second pluralities of the bus optical waveguides 102, 104 may not physically cross each other, and the crossing points can be associated with the top view (e.g., when the IOCS device 1901 is formed using two wafers similar to IOCS devices 600 or 700 described above). In some other embodiments, recovery optical waveguides 1902 and bus optical waveguides, and the first and second pluralities of the bus optical waveguides 102, 104 may cross each other and the crossing junctions may be configured to minimize or eliminate crosstalk between the crossing optical waveguides.

[0255] In some embodiments, the first, second, third, and fourth pluralities of mPDs 1912, 1914, 1916, 1918, may be electrically connected to an electronic circuit 1708 configured to receive sensor signals (detector signals) from these mPDs and use the sensor signals to determine the states of the plurality of primary optical switches 1904. The electronic circuit 1708 may be electrically connected to the plurality of primary optical switches 1904 and configured to control the ON/OFF state of the plurality of primary optical switches 1904 by providing activation signals to individual primary optical switches. The electronic circuit 1708 and its function in Figure 19B may comprise one or more features described above with respect to electronic circuit 1708 electrically connected to the IOCS devices 1701, 1702, 1703 and 1900.

[0256] Figure 20A schematically illustrates a top view of an example IOCS device 2000 having bus and recovery optical waveguides formed in two vertically separated waveguide layers and recovery optical switches for establishing recovery optical paths via the recovery optical waveguides. The IOCS device 2000 may comprise one or more features

described above with respect to IOCS devices 1900, 1901, 600 and 700. In some embodiments, the first plurality of bus optical waveguides 102 optically connected to the first plurality of optical ports 106 (e.g., the first plurality of bus optical waveguides 102) may be formed on a first wafer (e.g., a first waveguide layer formed on the first wafer) and the second plurality of bus optical waveguides 104 optically connected to the second plurality of optical ports 112 (e.g., the second plurality of bus optical waveguides 104) may be formed on a second wafer (e.g., a second waveguide layer formed on the second) or a second waveguide layer, where the second wafer and the second waveguide layer are vertically separated from the first wafer and the first waveguide layer (as shown and described above with respect to the IOCS devices 600 and 700). In some such embodiments, the plurality of primary optical switches 1904 and the first and second pluralities of the recovery optical switches 1905, 1906 may be formed over the first wafer and may comprise a shunt optical waveguide configured to controllably optically couple vertically separated optical waveguides formed in the first and second waveguide layers. In some embodiments the bus optical waveguides and recovery waveguides of the IOCS device 2000 may not physically cross each other, and the crossing points are where they cross in the top view.

[0257] In one embodiment shown in Figure 20A, first and second pluralities of the optical ports can be both located on the second wafer or second waveguide layer (e.g., above the first wafer). In some cases, the first plurality of optical ports 106 may be optically coupled to the first plurality of optical waveguides 102 (formed on the first wafer) by a plurality of interlayer optical couplers. In some implementations, an individual recovery optical waveguide may comprise a first section formed on the first wafer (or in a first waveguide layer), and a second section formed on the second wafer (or in a second waveguide layer), where the first and second sections are optically coupled by a recovery interlayer optical coupler. As such, the plurality of recovery optical waveguides may comprise a first plurality of recovery optical waveguide sections 1902a formed on the first wafer (or in a first waveguide layer), and a second plurality of recovery optical waveguide sections 1902b formed on the second wafer (or in the second waveguide layer), where the first and second pluralities of optical waveguide sections 1902a, 1902b, are optically coupled by a plurality of recovery interlayer optical couplers 2002.

[0258] In some examples, an interlayer optical coupler or a recovery interlayer optical coupler of the IOCS device 2000 may comprise a grating inter-layer optical coupler or a tapered waveguide inter-layer optical coupler (e.g., the tapered waveguide inter-layer coupler shown in Figures 11A-11C).

[0259] Figures 20B and 20C schematically illustrate a top view of a first wafer 2000a and second wafer 2000b of the IOCS device 2000, respectively. In some embodiments, the first wafer 2000a (Figure 20B) may comprise the first plurality of bus optical waveguides 102, the plurality of primary optical switches 1904, the first and second pluralities 1905, 1906, of the recovery optical switches, a first plurality of interlayer recovery optical coupler portions 2002a, a first plurality of interlayer optical coupler portions 802a, a first plurality of the recovery optical waveguide sections, the first plurality of mPDs 1912 (mPD A1,..., mPD Am), and the third plurality of mPDs 1916 (mPD C1,..., mPD Cm). In some embodiments, the second wafer 2000b (Figure 20C) may comprise the second plurality of bus optical waveguides 104, a second plurality of the recovery optical waveguide sections 1902b, a second plurality of interlayer optical coupler portions 802a, a second plurality of interlayer recovery optical coupler portions 2002b, the second plurality of mPDs 1912 (mPD B1,..., mPD Bm) 1914, and the fourth plurality of mPDs 1918 (mPD D1,..., mPD Dm). Once the two wafers are aligned and bonded (e.g., using the fabrication process described above with respect to Figures 6C or 7C). The first and second pluralities of the interlayer optical coupler portions 802a, 802b, may form the pluralities of the interlayer optical couplers 802 optically connecting the first plurality of bus optical waveguides 104 to the first plurality of optical ports 106, and The first and second pluralities of the interlayer recovery optical coupler portions 2002a, 2002b, may form the pluralities of the interlayer recovery optical couplers 2002 optically connecting the first and second pluralities of the recovery optical waveguide sections 1902a, 1902b.

[0260] In some embodiments, the IOCS device 2000 may comprise one or more features described above with respect to IOCS device 600 and the first and second wafers 2000a, 2000b may be used to fabricate the IOCS device 2000 based on the fabrication processes described in Figure 6C. In some embodiments, the IOCS device 2000 may comprise one or more features described above with respect to IOCS device 700 and the first and second wafers 2000a, 2000b may be used to fabricate the IOCS device 2000 based on the fabrication processes described in Figure 7C.

[0261] While the optical waveguides and ports of the OCIS device 2000 are fabricated on two vertically separated waveguide layers, embodiments are not so limited and some embodiments the first and second pluralities of the optical ports and bus optical waveguides of the IOCS device 1901 can be all formed on a single waveguide layer. In some embodiments, the IOCS device 1901 may comprise a fixed waveguide layer formed on a substrate, the fixed waveguide layer comprising the first and second pluralities of bus optical waveguides 102, 104, and the recovery optical waveguides 1902 and a suspended waveguide layer suspended over the fixed waveguide layer where the suspended waveguide layer is vertically separated from the fixed waveguide layer and mechanically supported by a plurality of conductive clamping structures. The suspended waveguide layer may comprise the first, second, and third pluralities of shunt optical waveguides associated with the primary optical switches 1904, the first plurality of recovery optical switches 1905, and the second plurality of recovery optical switches 1906, respectively. In some examples, a space between the fixed waveguide layer and the suspended waveguide layer can be substantially free of material other than the plurality of conductive clamping structures. In some examples, the conductive clamping structure is not electrically connected to any electronic circuit and the conductive regions associated with sensors and actuators of the optical switches. In some embodiments, the substrate may comprise a silicon wafer having a silicon dioxide layer including the fixed waveguide layer formed thereover. In some examples, the first, second, and third pluralities of shunt optical waveguides of the waveguides of the IOCS may comprise silicon nitride that has been deposited over a sacrificial material where the sacrificial material has been removed to suspend the suspended waveguide layer. In some examples, the first, second, and third pluralities of shunt optical waveguides of the waveguides of the IOCS may comprise a monocrystalline silicon transferred from a silicon-on-insulator (SOI) substrate by flip-chip bonding.

[0262] In some embodiments, an individual conductive clamping structure may be configured to clamp a longitudinal region of an individual ones of the first, second, and third pluralities of shunt optical waveguides between respective end regions of the individual shunt optical waveguide. In some cases, the individual conductive clamping structure may define a vertical distance between the fixed waveguide layer and the suspended waveguide layer. In some embodiments, the plurality of conductive clamping structures may be lithographically

defined and fabricated metallic pillars formed over the fixed waveguide layer and vertically extending through the suspended waveguide layer. In some embodiments, the metallic pillars can be formed of aluminum, copper, or other metals. In some examples, the plurality of conductive clamping structure may further comprise planar metallic layers connected to opposing ends of the plurality of metallic pillars.

[0263] In various implementations, any of the sensor configurations, recovery optical waveguides configurations, and recovery optical switches configurations described above with respect to the IOCS devices 1701, 1702, 1703, 1800, 1900, 1901 and 2000 may be implemented on or used in the IOCS devices 200, 201, 202, 203, 600, 700.

[0264] In various embodiments described above, an ON or OFF state of an optical switch may comprise an ON or OFF state of a shunt waveguide of the optical switch and vice versa.

[0265] In some embodiments, the optical switches of the IOCS devices 1701, 1702, 1703, 1800, 1900, 1901 and 2000 may comprise the optical switch described above with respect to switching cell (SC) 208 (Figures 3A-3C, 4, 5A-5B) or another type of MEMS optical switch.

[0266] In various embodiments, the actuators used in the optical switches of the IOCS devices 1701, 1702, 1703, 1800, 1900, 1901 and 2000 may comprise piezoelectric MEMS actuators.

Edge optical coupler

[0267] Figures 21A-21B schematically illustrate a front view (Figure. 21A) and a three-dimensional view (Figure. 21B) of an example edge optical coupler 2100 or fiber-to-chip optical coupler with backside etch. In some examples, the edge optical coupler 2100 may be configured to provide low-loss optical coupling between an optical fiber waveguide and an on-chip optical waveguide (e.g., a bus optical waveguide). In various applications, the optical fiber waveguide may comprise single mode and multimode optical fibers configured for operation, e.g., near or around 1310 nm or 1550 nm. For example, an optical fiber can be a single mode fiber having a mode field diameter of 9.2 microns, a high-NA fiber having a mode field diameter of 6.5 microns or 3.2 microns, a lensed fiber having a mode field diameter of 6.5 microns or 3.2 microns, however the embodiments are not so limited and other types of

optical fibers having different mode field diameters can be coupled to on-chip optical waveguides by the edge optical couplers 2100, 2110, and 2120 described below.

[0268] In one embodiment the edge coupler 2100 structure may comprise a top cladding layer 2102 may be formed on top side of a back (bottom) side etched substrate 2106. In some examples, the top cladding layer 2102 may comprise a material transparent (e.g., having an optical absorption coefficient less than 0.01 cm^{-1} , or less than 0.001 cm^{-1}) at a design wavelength of the edge coupler 2100 or within an operational wavelength range of the edge coupler 2100. In some implementations, the thickness h_1 of the top cladding layer can be from 4 to 8 microns. In some embodiments, edge coupler 2100 may be formed on a substrate (e.g., a silicon substrate) of an IOCS and may be configured to optically couple an optical fiber or another type of optical waveguide to a bus optical waveguide of the IOCS. In some embodiments, the edge coupler 2100 may comprise a tapered waveguide 2104 longitudinally extended from a waveguide end of the bus optical waveguide formed on the substrate (on which the IOCS is formed) to the edge of the substrate. In some embodiments, a lateral width of the tapered waveguide 2104 may increase from a first lateral width w_1 at the edge of the substrate 2106 to a second lateral width w_2 at the end of the bus optical waveguide formed on the substrate. However, embodiments are not so limited and in some embodiments, the first lateral width w_1 can be larger than the second lateral width w_2 . In various examples, the tapered waveguide 2104 can be linearly tapered or nonlinearly tapered from the second lateral width w_2 to the first lateral width w_1 . In some examples, w_2 can be substantially equal to a lateral width of the bus optical waveguide formed on the substrate. In various implementations, the tapered waveguide 2104 may be configured to adiabatically transform a transverse (lateral) optical mode profile from that of a first optical mode propagating in the bus optical waveguide to a transverse (lateral) optical mode profile closer to or matched with that of an optical fiber or another external waveguide. Accordingly, a variation of the lateral width of the tapered waveguide 2104 can be configured to adiabatically transform a transverse (lateral) optical mode profile between a bus optical waveguide of an IOCS and an external optical waveguide such as an optical fiber. In some examples, w_2 can be larger than w_1 by a factor from 1.1 to 1.5, from 1.5 to 2, from 2 to 3, from 3 to 4 or larger values. In some embodiments, w_2 can be from 100 to 300 nanometers (nm) and w_1 can be from 400 to 1000 nm. In some embodiments the tapered waveguide 2104 may comprise silicon nitride, silicon, or other materials (e.g., III-

V semiconductor materials). In some examples, the thickness of the tapered waveguide 2104 can be from 100 nm to 200 nm, from 200 nm to 300 nm, from 300 nm to 500 nm, from 500 nm to 700 nm or any ranges formed by these values or larger or smaller values.

[0269] In some examples, a region of the substrate 2106 below the tapered waveguide may be removed to form a slit (e.g., an air filed slit) 2103 below the tapered waveguide 2104 to modify an effective refractive index for light propagating the tapered waveguide 2104. In some implementations, slit 2103 may be extended in a longitudinal direction (e.g., parallel to y-axis) substantially parallel to tapered waveguide 2104. In some examples, a length of the slit 2103 (e.g., along y-axis) can be greater than 20%, 30%, 50%, or 80% of a length of the tapered waveguide 2104 or longer. In some examples, the length of the slit 2103 (e.g., along y-axis) can be substantially equal to the length of the tapered waveguide 2104.

[0270] In various implementations, a lateral width w_s of slit 2103 (along x-axis) can be from 5 to 10 microns, from 10 to 20 microns, from 20 to 30 microns, from 30 to 40 microns, from 40 to 50 microns, or any ranges formed by these values or larger or smaller values. In some implementations, w_s can be greater than the second lateral width (w_2) of the tapered waveguide. In some examples, the slit 2103 may be extended in a direction substantially parallel to the tapered waveguide 2104 and the bus optical waveguide optically connected to the tapered waveguide 2104 (e.g., parallel to y-axis). In some implementations, the first tapered waveguide may be formed in a top cladding layer 2102 formed on the substrate 2106. In some examples, the top cladding layer 2102 may comprising a first dielectric material having a first refractive index. In various implementations, the top cladding layer 2102 may comprise silicon dioxide or a polymer (e.g., an epoxy) having a refractive index that allows matching the mode field diameter at a first end of the tapered waveguide 2104 to that of an on-chip optical waveguide (e.g., a single mode waveguide) and at a second end of the tapered waveguide 2104 to that of the optical fiber or another waveguide. In some embodiments, the slit 2103 formed below the tapered waveguide 2104 may be filled with a second dielectric material having a second refractive index. In some implementations, the second refractive index can be lower than a refractive index of the substrate 2106. In some examples the first and second refractive indexes can be substantially equal. In some examples, the first and second dielectric materials can be substantially the same materials. Figures 21C-21D

schematically illustrate a front view (21C) and a three-dimensional view (21C) of another example of optical edge coupler 2120. The optical edge coupler 2120 may comprise one or more features described above with respect to the optical edge coupler 2100 however the slit 2103 below the tapered waveguide of the optical edge coupler 2120 may be filled with the second dielectric material to form a bottom cladding layer 2108. In some examples, the second dielectric material may have a refractive index substantially equal to or matched with the refractive index of the first dielectric material.

[0271] Figures 21E-21F schematically illustrate a front view (21E) and a three-dimensional view (21F) of yet another example optical edge coupler 2140. The optical edge coupler 2140 may comprise one or more features described above with respect to the optical edge coupler 2100 however a bottom cladding layer 2110 may be formed on a bottom surface of the top cladding layer 2102 below the tapered waveguide 2104 and on the sidewalls of the slit 2103. In some embodiments, the bottom cladding layer 2110 may comprise the second dielectric material. As such the bottom cladding layer 2110 may divide an internal volume of the slit 2103 into two regions having different refractive indices (e.g., corresponding to air and the second dielectric material). In some cases, a first thickness h_4 (along x-axis) of a portion of the bottom cladding layer 2110 formed on a bottom surface of the top cladding layer 2102 can be substantially equal or different from a thickness h_5 (along y-axis) of the bottom cladding layer 2110 formed on the sidewalls of the slit 2103. In some examples h_5 can be larger than h_4 . In various implementations, h_4 and h_5 can be from 5 to 10 microns, from 10 to 20 microns, from 20 to 30 microns, from 30 to 40 microns, from 40 to 50 microns, from 50 to 100 microns or any ranges formed by these values or larger or smaller values. In various implementations, a vertical spacing (e.g., along z-axis) between the tapered waveguide 2104 and a bottom surface of the top cladding layer 2102 can be from 1 to 2 microns, from 2 to 3 microns, from 3 to 4 microns, or any ranges formed by these values or larger or smaller values.

[0272] In various implementations, the tapered waveguide 2104 may be configured to adiabatically transform a transverse optical power distribution (in a plane perpendicular to the direction of propagation of light, e.g., parallel to y-axis) from a narrower end of the tapered waveguide 2104 optically connected (or coupled) to bus optical waveguide to a wider end the tapered waveguide 2104 optically connected (or coupled) to an optical fiber (or a waveguide formed on a chip), and vice versa.

[0273] In various implementations, the width w_s of the slit 2103 (parallel to x-axis), the first dielectric material of top cladding layer 2102, the second dielectric material filling or coating the slit 2103, h_3 , and/or h_5 may be configured improve the adiabatic transformation of the transverse optical power distribution from a distribution matched or closer to that of the optical fiber (or another optical waveguide) to a distribution matched or closer to that of the bus optical waveguide, and thereby reduce optical coupling loss associated with optical mode mismatch between the bus optical waveguide and the optical fiber.

[0274] In various embodiments, one or more features (e.g., geometrical properties of the structure and/or optical properties of materials) may be designed, selected, or otherwise configured based at least in part on a design wavelength or an operational wavelength range of the edge couplers 2100, 2120, 2140,

[0275] In some embodiments, a bus optical waveguide and each one of the edge couplers 2100, 2120, 2140, may be monolithically fabricated on a common substrate such an external optical waveguide (e.g., an optical fiber waveguide) can be optically coupled to the bus optical waveguide with an optical efficiency greater than 5%, 10%, 20%, 50% or larger values. In some implementations, at least a portion of the bus optical waveguide and edge coupler can be co-fabricated on the common substrate.

[0276] In various implementations, an optical port of the IOCS devices 200, 201, 202, 203, 600, 700, 1701, 1702, 1703, 1800, 1900, 1901 and 2000 described above may comprise the edge coupler 2100, 2120, or 2140.

Edge Coupler Interposer

[0277] In various applications, a larger size (e.g., diameter) of waveguides (e.g., optical fiber) that receive and/or transmit light from/to the on-chip optical waveguides of an integrated photonic chip (e.g., bus optical waveguides of an IOCS) may not allow a high-density arrangement of the bus optical waveguides and the corresponding optical ports near an edge of the integrated photonic chip. In some embodiments, an edge coupler interposer (e.g., a fiber-to-chip interposer) may allow coupling light between two arrays of waveguides having different pitches. Such edge coupler interposers may be positioned between an array of optical ports optically connected to a first array of waveguides having a first pitch and formed on the integrated photonic chip and a second array of waveguides having a second pitch larger than the first pitch. In some examples, the array of optical ports and the first array of waveguides may comprise the optical ports and bus optical waveguides of IOCS and the second

array of waveguides may comprise an array of optical fibers. As such when an edge coupler interposer is used between IOCS and the array of optical fibers, the pitch of the optical fiber array does not limit the pitch of the array of the optical ports thereby allowing fiber coupling to high-density IOCS devices. In some embodiments, the first pitch of the optical ports and/or bus optical waveguides of a high-density IOCS can be 2 times, 3 times, 4 times, 5 times, or 10 times smaller the second pitch of the optical fiber array coupled to the IOCS via a fiber-to-chip interposer. Figure 18 shows a top view schematic of an integrated photonic MEMS OCS.

[0278] Figures 22A-22B schematically illustrate a front view (22A) and a three-dimensional view (22B) of an edge coupler interposer 2200 comprising a one-dimensional (1D) first array of optical ports (or waveguide facets) 2201, configured to be optically coupled to optical ports of a photonic chip, and a two-dimensional (2D) second array of optical ports (or waveguide facets) 2202 configured to be optically coupled to a two-dimensional (2D) array of optical fibers. In some embodiments, the edge coupler interposer 2200 may be configured optically to a 1D array of optical ports arranged along a lateral direction (e.g., parallel to the x-axis) at an edge of an IOCS chip to a 2D array of optical fibers arranged along the lateral direction and a vertical direction (e.g., along z-axis). In some embodiments, 1D array of optical ports of the IOCS can be periodic array and have a first pitch, and 2D array of optical fibers can be periodic and have a second pitch, along the lateral direction, where the second pitch is larger than the first pitch. In some embodiments the first pitch can be equal or smaller than 50% of the second pitch. Advantageously, by reducing the first pitch to half or smaller than half of the second pitch the edge coupler interposer 2200 may increase the bus optical density and optical switch density of a fiber-coupled IOCS device. The edge coupler interposer 2200 may further comprise a plurality of optical waveguides extending in a longitudinal direction (e.g., along y-axis) from the first array of optical ports 2201, to the second array of optical ports 2202 to optically couple the first array of optical ports 2201 to the two-dimensional (2D) second array of optical ports 2202.

[0279] With continued reference to Figures 22A, 22B, in some embodiments, the edge coupler may comprise a first array (e.g., 1D array) of waveguide facets 2201 (also referred to as first plurality optical ports) at first periodic positions (first pitch, p_1) along the first lateral direction (e.g., along x-axis), a first longitudinal position (e.g., along y-axis) and a common vertical position (e.g., along z-axis), and a 2D array of waveguide facets 2202 at a second longitudinal position, where 2D array of waveguide facets comprises second and third 1D arrays of waveguide facets vertically separated and forming a 1D array of vertically separated waveguide facet pairs at second

periodic positions (e.g., second pitch, p_2) along the lateral direction. In some embodiments, first and second waveguide facets 2201a, 2201b of the first array of waveguide facets 2201 can be optically coupled by a first and second waveguides 2204a, 2204b to third and fourth waveguide facets 2202a, 2202b of a vertically separated waveguide facet pair of the array of vertically separated waveguide facet pairs 2202, respectively. In some examples, the first and second waveguide facets 2201a, 2201b, can be nearest neighboring waveguide facets of the first array of waveguide facets 2201. In some implementations, the first pitch (p_1) of the first 1D array of waveguide facets 2201 can be at least two times smaller than the second pitch (p_2) of vertically separated waveguide facet pairs. In some implementations, first and second optical waveguides 2204a, 2204b, may extend in the longitudinal direction (e.g., along y-axis) from the first longitudinal position to second longitudinal position to optically couple the first waveguide facet 2201a to the third waveguide facet 2202a and the second waveguide facet 2201b to the fourth waveguide facet 2202b. In some implementations, p_1 can be from 40 to 250 microns and p_2 can be substantially two times p_1 or larger values.

[0280] In the example shown in Figure 22B, the 2D array of waveguide facets 2202 comprise two 1D arrays or two rows however the embodiments are not so limited and an edge interposer similar to the edge interposer 2200 may include a larger number of rows.

[0281] In some embodiments, the vertical separation (L_z) between vertically separated waveguide facet pair of the array of vertically separated waveguide facet pairs 2202, can be from 80 to 500 microns.

[0282] In some embodiments, a difference L_y between the first and second longitudinal positions can be from 10 microns to 100 microns, from 100 microns to 1000 microns, from 1 millimeter to 2 millimeters or larger than the second longitudinal position.

[0283] Figure 22C schematically illustrates a top view of an IOCS 2220 having two sets of ports (labeled $A_1, \dots, A_m$, and $B_1, \dots, B_n$) along two different edges and two edge coupler interposers 2200a, 2200b, similar to edge coupler interposer 2200 each aligned and coupled to a different one of the set of ports. In some cases, a first edge coupler interposer 2200a may be aligned to a first edge of the IOCS 2220 to optically couple to a first plurality of optical ports and the corresponding first plurality of bus optical waveguides of the IOCS 2220 to a first plurality of optical fibers, and a second edge coupler interposer 2200b may be aligned to a second edge of the IOCS 2220 to optically couple to a second plurality of optical ports and the

corresponding second plurality of bus optical waveguides of the IOCS 2220 to a second plurality of optical fibers. In various implementations, IOCS 2220 may comprise one or more features described above with respect to IOCS devices 200, 201, 202, 203, 600, 700, 1701, 1702, 1703, 1800, 1900, 1901 and 2000.

Electronic connection and controls

[0284] The IOCS devices described above may be controlled by integrated circuits fabricated on a CMOS chip by applying control voltages to the MEMS actuators to activate the optical switches and to put an optical switching cell in an ON state.

[0285] In some embodiments, the electrodes of MEMS actuators can be connected to the corresponding outputs of the CMOS chip by through-silicon vias (TSV). In some embodiments the electrodes of MEMS actuators can be connected to the corresponding outputs of the CMOS chip by through-oxide vias (TOV) or by flip-chip bonding. In various implementations, the TSV vias and/or TOV may be fabricated on any of the two wafers or substrates.

[0286] In some embodiments, the electronic circuits and systems (e.g., electric circuit 1708) may comprise a non-transitory memory storing machine readable instructions and an electronic processor in communication with the non-transitory memory. In various implementations, the electronic processor may be configured to execute the machine instructions stored in the memory to provide the functionalities described above with respect to controlling optical switches, determining states of the optical switches based on sensor signals, establishing a recovery optical path to bypass a malfunctioning optical switch, and the like.

Example Embodiments

[0287] Various additional example embodiments of the disclosure can be described by the following examples:

Example Embodiment I

[0288] Example 1. An integrated optical circuit (IOC) comprising:
a first waveguide layer having formed therein a first bus optical waveguide;

a second waveguide layer having formed therein a second bus optical waveguide;

an optical switch comprising a shunt waveguide disposed in a gap vertically between the first and second bus optical waveguide layers and configured to moveably couple the first bus optical waveguide and the second bus optical waveguide upon activation; and

a pair of optical alignment structures formed in the first and second waveguide layers, wherein the optical alignment structures are optically aligned within a predetermined tolerance to correspondingly align the first and second waveguide layers and the optical switch within a predetermined tolerance such that when activated, the shunt waveguide optically couples first and second bus optical waveguides to redirect light therebetween.

[0289] Example 2. The integrated optical circuit of any one of the above Examples, wherein the pair of optical alignment structure comprises a loop-back waveguide structure having two portions each formed in one of the first or second waveguide layers.

[0290] Example 3. The integrated optical circuit of Example 2, wherein a first portion of the loop-back waveguide structure comprises two optically isolated waveguide sections and the second portion of the loop-back waveguide structure comprises a loop-back waveguide section configured to be optically coupled to the two optically isolated waveguide sections via two inter-layer optical couplers.

[0291] Example 4. The integrated optical circuit of Example 3, wherein the inter-layer optical couplers comprise grating couplers.

[0292] Example 5. The integrated optical circuit of Example 3, wherein the inter-layer optical couplers comprise tapered waveguide couplers.

[0293] Example 6. The integrated optical circuit of any one of the above Examples, wherein the pair optical alignment structure comprises a pair of alignment marks each formed in one of the first or second waveguide layers.

[0294] Example 7. The integrated optical circuit of any one of the above Examples, further comprising a physical alignment structure comprising a protrusion extending between the first and second waveguide layers, the protrusion mechanically engaged with an opening.

[0295] Example 8. The integrated optical circuit of Example 7, wherein the protrusion has a semispherical, a cylindrical, or a rectangular shape, and the opening comprises a V-groove, a cylindrical hole, or a rectangular hole.

[0296] Example 9. The integrated optical circuit of any one of the above Examples, wherein the pair of optical alignment structures are formed outside of a region within which the optical switch is formed.

Example Embodiment II

[0297] Example 1. A method of aligning two wafers comprising integrated photonic devices, the method comprising:

providing a first wafer, the first wafer comprising:

a first waveguide layer having formed therein a first bus optical waveguide,

an optical switch structure comprising a shunt waveguide configured to moveably optically couple the first bus optical waveguide to a second bus optical waveguide upon activation to redirect light between the first and second bus optical waveguides, and

a first one of a pair of optical alignment structures comprising a first waveguiding structure;

providing a second wafer, the second wafer comprising:

a second waveguide layer having formed therein the second bus optical waveguide, and

a second one of the pair of optical alignment structures comprising a second waveguiding structure;

providing optical input power to the first waveguiding structure of the first one of the pair of optical alignment structures;

positioning the second wafer with respect to the first wafer such that the second waveguiding structure is positioned above the first waveguiding structure;

measuring an output optical power output by the second waveguiding structure as a result of optical coupling between the first and second waveguiding structures;

aligning the first wafer with respect to the second wafer based on the measured output optical power; and

wherein the measured output optical power directly correlates to an optical coupling strength between the first and second optical waveguides, when the optical switch structure is activated.

[0298] Example 2. The method of any one of the above Examples, wherein the first waveguiding structure comprises a pair of optically isolated waveguides and the second waveguiding structure comprises a loop back waveguide section.

[0299] Example 3. The method of any one of the above Examples, wherein the optical alignment structure further comprises inter-layer optical couplers configured to optically couple the first and second waveguiding structures.

[0300] Example 4. The method of Example 3, wherein the inter-layer optical couplers comprise grating couplers.

[0301] Example 5. The method of Example 3, wherein the inter-layer optical couplers comprise tapered waveguide couplers.

[0302] Example 6. The method of Example 5, wherein aligning the first wafer with respect to the second wafer based on the measured output optical power comprises aligning the first wafer with respect to the second wafer in a first direction.

[0303] Example 7. The method of Example 6, wherein the first wafer further comprises a first one of a second pair of optical alignment structures comprising a third waveguiding structure and the second wafer comprises a second one of the second pair of optical alignment structures comprising a fourth waveguiding structure.

[0304] Example 8. The method of Example 7, wherein the method further comprises:

providing second optical input power to the third waveguiding structure of the first one of the pair of the second optical alignment structures;

positioning the second wafer with respect to the first wafer such that the fourth waveguiding structure is positioned above the third waveguiding structure;

measuring a second output optical power output by the third waveguiding structure as a result of optical coupling between the third and fourth waveguiding structures;

aligning the first wafer with respect to the second wafer based on the measured second output optical power.

[0305] Example 9. The method of Example 8, wherein aligning the first wafer with respect to the second wafer based on the measured second output optical power comprises aligning the first wafer with respect to the second wafer in a second direction.

[0306] Example 10. The method of Example 9, wherein the first direction is substantially perpendicular to the first direction.

[0307] Example 11. The method of Example 10, wherein the third waveguiding structure comprises a second pair of optically isolated waveguides and the third waveguiding structure comprises a second loop back waveguide section, and the second optical alignment structure further comprises second inter-layer optical couplers configured to optically couple the third and fourth waveguiding structures.

[0308] Example 12. The method of Example 11, wherein the second inter-layer optical couplers comprise tapered waveguide couplers.

[0309] Example 13. The method of Example 12, wherein the first wafer further comprises a first one of a third pair of optical alignment structures comprising a fifth waveguiding structure and the second wafer comprises a second one of the third pair of optical alignment structures comprising a sixth waveguiding structure.

[0310] Example 14. The method of Example 13, wherein the method further comprises:

providing third optical input power to the fifth waveguiding structure of the first one of the pair of the third optical alignment structures;

positioning the second wafer with respect to the first wafer such that the sixth waveguiding structure is positioned above the third waveguiding structure;

measuring a third output optical power output by the fifth waveguiding structure as a result of optical coupling between the fifth and sixth waveguiding structures;

aligning the first wafer with respect to the second wafer based on the measured third output optical power.

[0311] Example 15. The method of Example 13, wherein the fifth waveguiding structure comprises a second pair of optically isolated waveguides and the sixth waveguiding structure comprises a third loop back waveguide section, and the third optical

alignment structure further comprises third inter-layer optical couplers configured to optically couple the third and fourth waveguiding structures.

[0312] Example 16. The method of Example 15, wherein the third inter-layer optical couplers comprise grating couplers.

Example Embodiment III

[0313] Example 1. An integrated optical circuit (IOC) comprising:
a first waveguide layer having formed therein a first bus optical waveguide;
a second waveguide layer having formed therein a second bus optical waveguide;
an optical switch comprising a shunt waveguide disposed in a gap vertically between the first and second bus optical waveguide layers and configured to moveably couple the first bus optical waveguide and the second bus optical waveguide upon activation; and
a pair of physical alignment structures formed on the first and second waveguide layers, wherein the physical alignment structures are physically coupled to align the first and second waveguide layers and the optical switch within a predetermined tolerance such that when activated, the shunt waveguide optically couples first and second bus optical waveguides to redirect light therebetween.

Example 2. The integrated optical circuit of any one of the above Examples, wherein the pair of physical alignment structures comprises first and second physical alignment structures.

Example 3. The integrated optical circuit of Example 2, wherein the first or the second physical alignment structure comprises a protrusion.

Example 4. The integrated optical circuit of Example 3, wherein the protrusion comprises a semi-sphere or a pillar having circular or a rectangular cross-section.

Example 5. The integrated optical circuit of Example 3, wherein the protrusion comprises a polymeric material.

Example 6. The integrated optical circuit of Example 3, wherein the first or second physical alignment structure comprises an opening.

Example 7. The integrated optical circuit of Example 6, wherein the opening comprises a v-groove, an etched pyramid, or an etched cuboid.

Example 8. The integrated optical circuit of Example 6, wherein the opening and the first waveguide layer, and the optical switch are formed on a first common substrate.

Example 9. The integrated optical circuit of Example 8, wherein the protrusion and the second waveguide layer are disposed on a second common substrate.

Example 10. The integrated optical circuit of Example 8, wherein the opening is formed in a region of the first common substrate outside of a region of the first common substrate within which the optical switch is formed.

Example Embodiment IV

[0314] Example 1. A method of aligning two wafers comprising integrated photonic devices, the method comprising:

providing a first wafer, the first wafer comprising:

a first waveguide layer having formed therein a first bus optical waveguide,

an optical switch structure comprising a shunt waveguide configured to moveably optically couple the first bus optical waveguide to a second bus optical waveguide upon activation to redirect light between the first and second bus optical waveguides, and

a first physical alignment structure of a pair of physical alignment structures;

providing a second wafer, the second wafer comprising:

a second waveguide layer having formed therein the second bus optical waveguide, and

a second physical alignment structure of the pair of physical alignment structures, the second physical alignment structure configured to physically couple to the first physical alignment structure;

aligning the first and second wafers laterally to align the first physical alignment structure over the second physical alignment structure within a predetermined tolerance; and

vertically engaging the first and second physical alignment structures such that, when activated, the shunt waveguide optically couples first and second bus optical waveguides to redirect light therebetween.

[0315] Example 2. The method of any one of the above Examples, wherein when activated a first end portion of the shunt waveguide moves toward the first bus optical waveguide and a second end portion of the shunt waveguide moves toward the second bus optical waveguide.

[0316] Example 3. The method of any one of the above Examples, wherein the first wafer comprises an optical switch comprising the shunt waveguide and a microelectromechanical system (MEMS) actuator configured to move movable portions of the shunt waveguide.

[0317] Example 4. The method of any one of the above Examples, wherein the first or the second physical alignment structure comprises a protrusion.

[0318] Example 5. The method of Example 4, wherein the protrusion comprises a semi-sphere or a pillar having circular or rectangular cross-section.

[0319] Example 6. The method of Example 4, wherein the protrusion is disposed on the first or second wafer.

[0320] Example 7. The method of Example 6, wherein the protrusion comprises a polymeric material.

[0321] Example 8. The method of any one of the above Examples, wherein the first or second physical alignment structure comprises an opening.

[0322] Example 9. The method of Example 8, wherein the opening comprises a v-groove, an etched pyramid, or an etched cuboid.

Example Embodiment V

[0323] Example 1. A method of aligning two wafers comprising integrated photonic devices, the method comprising:

providing a first wafer, the first wafer comprising:

a first waveguide layer having formed therein a first bus optical waveguide,

an optical switch structure comprising a shunt waveguide configured to moveably optically couple the first bus optical waveguide to a second bus optical waveguide upon activation to redirect light between the first and second bus optical waveguides, and

a first physical alignment structure of a pair of physical alignment structures;

providing a second wafer, the second wafer comprising:

a second waveguide layer having formed therein the second bus optical waveguide, and

a second physical alignment structure of the pair of physical alignment structures, the second physical alignment structure configured to physically couple to the first physical alignment structure;

providing a microbead between the first and second physical alignment structures to mechanically link first and second physical alignment structures;

aligning the first and second wafers laterally to align the first physical alignment structure over the second physical alignment structure within a predetermined tolerance; and

vertically engaging the first and second physical alignment structures via the microbead such that, when activated, the shunt waveguide optically couples first and second bus optical waveguides to redirect light therebetween.

[0324] Example 2. The method of any one of the above Examples, wherein when activated a first end portion of the shunt waveguide moves toward the first bus optical waveguide and a second end portion of the shunt waveguide moves toward the second bus optical waveguide.

[0325] Example 3. The method of any one of the above Examples, wherein the first wafer comprises an optical switch comprising the shunt waveguide and a microelectromechanical system (MEMS) actuator configured to move movable portions of the shunt waveguide.

[0326] Example 4. The method of any one of the above Examples, wherein the first and the second physical alignment structure comprise first and second openings.

[0327] Example 5. The method of Example 4, wherein the opening comprises a V-groove, an etched pyramid, or an etched cuboid.

[0328] Example 6. The method of any one of the above Examples, wherein the microbead comprises a polymer.

[0329] Example 7. The method of any one of the above Examples, wherein the microbead has a spherical shape.

Example Embodiment VI

[0330] Example 1. An integrated optical circuit (IOC) comprising:
a first waveguide layer formed on a substrate, the first waveguide layer having formed therein a first bus optical waveguide;

a second waveguide layer having formed therein a second bus optical waveguide;

an optical switch comprising a shunt optical waveguide disposed in a gap vertically between the first and second bus optical waveguide layers and configured to moveably optically couple the first bus optical waveguide and the second bus optical waveguide upon activation to redirect light between the first and second bus optical waveguides; and

a plurality of vertical vias serving as mechanical anchors and electrical connections between the first and second waveguide layers to fixedly suspend the second waveguide layer above the first waveguide layer, the vertical vias formed of a material that is etch-selective to a sacrificial material removed from the gap during fabrication.

[0331] Example. 2 The integrated optical circuit of any one of the above Examples, wherein an anchor of the plurality of anchors is vertically extended from the first waveguide layer to the second waveguide layer, the anchor having a cross-sectional area smaller than 100 square microns.

[0332] Example. 3 The integrated optical circuit of Example 2, wherein the anchor does not include a bonded interface or a discontinuity from the first waveguide layer to the second waveguide layer.

[0333] Example. 4 The integrated optical circuit of any one of the above Examples, wherein the shunt optical waveguide is configured to be optically isolated from the first and second bus optical waveguides when the switch is an OFF state, and to optically couple the first and second bus optical waveguides when the optical switch is in an ON state.

[0334] Example. 5 The integrated optical circuit of any one of the above Examples, wherein the substrate comprises a wafer.

[0335] Example. 6 The integrated optical circuit of any one of the above Examples, wherein the second waveguide layer consist of a support layer on which the second bus optical waveguide is formed.

[0336] Example. 7 The integrated optical circuit of any one of the above Examples, wherein a thickness of the second waveguide layer is less than 800 microns.

[0337] Example 8. The integrated optical circuit of any one of the above Examples, wherein the shunt optical waveguide is mechanically supported by a clamping structure.

[0338] Example 9. The integrated optical circuit of Example 8, wherein spaces between the first waveguide layer and the shunt optical waveguide are substantially free of material other than the plurality of anchors and the clamping structure.

[0339] Example 10. The integrated optical circuit of any one of the above Examples, wherein spaces between the shunt optical waveguide and the second waveguide layer are substantially free of material other than the plurality of anchors.

[0340] Example 11. The integrated optical circuit of any one of the above Examples, wherein when the optical switch is in an ON state more than 80% of optical power propagating in the first optical waveguide is coupled to the second optical waveguide.

[0341] Example 12. The integrated optical circuit of any one of the above Examples, wherein the optical switch further comprises at least one microelectromechanical systems (MEMS) actuator configured to actuated the shunt optical waveguide to optically couple a first end region thereof to the first bus optical waveguide and a second end region thereof to the second bus optical waveguide.

[0342] Example 13. The integrated optical circuit of Example 12, wherein the at least one MEMS actuator comprises a first electrostatic actuator configured to move the first end region of the shunt optical waveguide and a second electrostatic actuator configured to move the second end region of the shunt optical waveguide.

[0343] Example 14. The integrated optical circuit of any one of the above Examples, wherein an end of the first bus optical waveguide and an end of the second bus optical waveguide each comprise an optical port configured to transmit light to, or receive light from, an external optical waveguide or an external optical device.

[0344] Example 15. The integrated optical circuit of Example 14, wherein the external optical waveguide comprises an optical fiber and the optical port comprises a fiber-to-waveguide coupler.

[0345] Example 16. The integrated optical circuit of Example 15, wherein the fiber-to-waveguide coupler comprises a surface optical coupler.

[0346] Example 17. The integrated optical circuit of any one of Examples 1-16, wherein an end of the first bus optical waveguide comprises an optical port and other end of the first bus optical waveguide is optically coupled to an integrated optical device on the first waveguide layer, or an integrated optical device on the second waveguide layer.

[0347] Example 18. The integrated optical circuit of any one of the above Examples, wherein both ends of the first bus optical waveguide each comprise an optical port.

[0348] Example 19. The integrated optical circuit of any one of the Examples 17 and 18, further comprising one or more inter-layer optical couplers configured to optically couple one or both ends of the second bus optical waveguide to one or more optical ports formed on the first waveguide layer.

[0349] Example 20. The integrated optical circuit of any one of the above Examples, wherein both ends of the second bus optical waveguide each comprise an optical port.

[0350] Example 21. The integrated optical circuit of any one of the above Examples, wherein an end of the second bus optical waveguide comprises an optical port and other end of the second bus optical waveguide is optically coupled to an integrated optical device on the second waveguide layer or an integrated optical device on the first waveguide layer via an inter-layer optical coupler.

[0351] Example 22. The integrated optical of any one of the Examples 20 and 21, further comprising one or more inter-layer optical couplers configured to optically couple one or both ends of the first optical waveguide to one or more optical ports formed on the second waveguide layer.

[0352] Example 23. The integrated optical circuit of any one of Examples 17-22, wherein the optical port or the one or more optical ports comprise a fiber-to-waveguide coupler.

[0353] Example 24. The integrated optical circuit of any one of Examples above, further comprising a first alignment structure in the first waveguide layer or on the substrate and a second alignment structure in the second waveguide layer, the first alignment structure physically or optically aligned with respect to the second alignment structure.

[0354] Example 25. The integrated optical circuit of Example 24, wherein the first alignment structure comprises a first portion of a loop-back waveguide structure and the second alignment structure comprises a second portion of the loop-back waveguide structure.

[0355] Example 26. The integrated optical circuit of Example 25, wherein the first portion of a loop-back waveguide structure comprises two optically isolated waveguide sections and the second portion of the loop-back waveguide structure comprises a loop-back waveguide section configured to be optically coupled to the two optically isolated waveguide sections via two inter-layer optical couplers.

[0356] Example 27. The integrated optical circuit of Example 24, wherein the first and second alignment structures comprise a matched pair of self-alignment structures configured to be mechanically engaged with each other.

[0357] Example 28. The integrated optical circuit of Example 27, wherein the matched pair of self-alignment structures comprise a pin or protrusion and a matching hole or opening.

[0358] Example 29. The integrated optical circuit of Example 28, wherein the protrusion or pin has a semispherical, a cylindrical, or a rectangular shape, and the hole or opening comprises a V-groove, a cylindrical hole, or a rectangular hole.

[0359] Example 30. The integrated optical circuit of any one of the above Examples, wherein the optical alignment structure comprises a pair of alignment marks each formed in one of the first or second waveguide layers.

Example Embodiment VII

[0360] Example 1. A method of fabricating an integrated optical circuit (IOC) device, the method comprising:

fabricating a first wafer comprising:

lithographically patterning to form a first bus optical waveguide extending within a first waveguide layer on a front side of a first substrate, and

forming on the first substrate an optical switch structure comprising a shunt optical waveguide at least partly fixedly buried in a sacrificial material;

fabricating a second wafer comprising lithographically patterning to form a second optical bus waveguide extending within a second waveguide layer on a front side of a second substrate;

bonding the front surface of the second wafer to a front surface the first wafer; removing the second substrate;

forming a plurality of vertical vias through the second waveguide layer and further through the sacrificial material, the vertical vias serving as mechanical anchors and electrical connections between the first and second waveguide layers; and

selectively removing the sacrificial material to release the shunt optical waveguide to configure the shunt optical waveguide to moveably optically couple the first bus optical waveguide and the second bus optical waveguide upon activation to redirect light between the first and second bus optical waveguides.

[0361] Example 2. The method of any one of the above Examples, wherein forming the optical switch structure comprises forming a microelectromechanical structure and selectively removing the sacrificial material comprises forming MEMS actuators by releasing the microelectromechanical structure.

[0362] Example 3. The method of any one of the above Examples, wherein bonding the second substrate to the first substrate comprises aligning the first substrate with respect to the second substrate such that an end portion of the shunt optical waveguide is substantially parallel to the second optical waveguide.

[0363] Example 4. The method of any one of the above Examples, wherein the first substrate comprises a first portion of an alignment structure, the second substrate

comprises a second portion of the alignment structure, and aligning the second substrate with respect to the first substrate comprises aligning the second portion of the alignment structure to the first portion of the alignment structure.

[0364] Example 5. The method of Example 4, wherein the first portion of the alignment structure comprises a pair of optically isolated waveguides and the second portion of the alignment structure comprises a loop back waveguide section configured to optically couple the pair of optically isolated waveguides when the first and second substrates are substantially aligned.

[0365] Example 6. The method of Example 5, wherein the alignment structure further comprises inter-layer optical couplers configured to couple light between the pair of optically isolated waveguides and the loop back waveguide section.

[0366] Example 7. The method of Example 6, wherein the inter-layer optical couplers comprise grating couplers.

[0367] Example 8. The method of Example 6, wherein the inter-layer optical couplers comprise tapered optical waveguides.

[0368] Example 9. The method of Example 4, wherein aligning the second substrate with respect to the first substrate comprises aligning the second substrate with respect to the first substrate in a first direction.

[0369] Example 10. The method of Example 9, wherein aligning the second substrate with respect to the first substrate further comprises aligning the second substrate with respect to the first substrate in a second direction.

[0370] Example 11. The method of Example 10, wherein the first substrate further comprises a first portion of a second alignment structure, the second substrate comprises a second portion of the second alignment structure, and aligning the second substrate with respect to the first substrate in the second direction comprises aligning the second portion of the second alignment structure to the first portion of the second alignment structure.

[0371] Example 12. The method of Example 10, wherein the first direction is substantially perpendicular to the second direction.

[0372] Example 13. The method of Example 4, wherein one of the first and second portions of the alignment structure comprises a plurality of protrusions and the other one comprises a plurality of openings configured to receive respective protrusions.

[0373] Example 14. The method of Example 13, wherein bonding the second substrate to the first substrate further comprises positioning the first and second substrates such that individual protrusions of the plurality of alignment protrusions are inserted into or are mechanically engaged with respective individual openings of the plurality of openings.

[0374] Example 14. The method of Example 13, wherein an individual protrusion of the plurality of protrusions comprises a semi-sphere or a pillar having circular or rectangular cross-section.

[0375] Example 15. The method of Example 13, wherein an individual protrusion of the plurality of protrusions comprises a polymeric material.

[0376] Example 16. The method of Example 13, wherein an individual opening of the plurality of openings comprises a v-groove, an etched pyramid, or an etched cuboid.

[0377] Example 17. The method of Example 4, wherein the first portion of the alignment structure comprises a first plurality of openings and the second portion of the alignment structure comprises a second plurality openings.

[0378] Example 18. The method of Example 17, wherein first and second pluralities of alignment openings comprise one or both of etched pyramids and v-grooves.

[0379] Example 19. The method of Example 18, wherein bonding the second substrate to the first substrate further comprises providing a plurality of microbeads between the first and second substrates and positioning the first and second substrates such that individual microbeads provide mechanical linkage between individual openings of the first plurality of alignment openings and the respective individual openings of the second plurality of openings.

[0380] Example 20. The method of any one of the above Examples, wherein bonding the second substrate to the first substrate comprises bonding a first mechanical stopper to a second mechanical stopper.

[0381] Example 21. The method of any one of the above Examples, wherein bonding the second substrate to the first substrate comprises bonding a first bonding pad to a second bonding pad.

[0382] Example 22. The method of Example 2, wherein selectively removing the sacrificial material comprises removing the sacrificial material from the microelectromechanical structure to release a MEMS actuator.

Example Embodiment VIII

[0383] Example 1. An integrated optical circuit (IOC) device comprising:
a first waveguide layer formed on a first substrate, first waveguide layer having formed therein a first bus optical waveguide;
a second waveguide layer formed on a second substrate, the second waveguide layer having formed therein a second bus optical waveguide;
an optical switch comprising a shunt optical waveguide disposed in a gap vertically between the first and second bus optical waveguide layers and configured to moveably optically couple the first bus optical waveguide and the second bus optical waveguide upon activation to redirect light between the first and second bus optical waveguides; and
a plurality of mechanical stoppers vertically extending between the first and second substrates, wherein each mechanical stopper has a first mechanical stopper portion formed on the first substrate and a second mechanical stopper portion formed on the second substrate,
wherein the second substrate is bonded to the first substrate using the mechanical stoppers such that the first bus optical waveguide is vertically separated from the second bus optical waveguide by a distance defined by the mechanical stopper.

[0384] Example 2. The integrated optical circuit (IOC) device of any one of the above Examples, wherein the first waveguide layer comprises a first buffer layer between the first optical waveguide and the first substrate.

[0385] Example 3. The integrated optical circuit (IOC) device of any one of the above Examples, wherein the second waveguide layer comprises a second buffer layer between the second bus optical waveguide and the second substrate.

[0386] Example 5. The integrated optical circuit (IOC) device of any one of the above Examples, wherein the first mechanical stopper portion is bonded to the second mechanical stopper portion.

[0387] Example 6. The integrated optical circuit (IOC) device of any one of the above Examples, wherein first mechanical stopper portion is in contact with but it is not bonded to the second mechanical stopper portion.

[0388] Example. 7 The integrated optical circuit of any one of the above Examples, wherein the first and second mechanical stopper portions have cross-sectional areas larger than 10 square microns.

[0389] Example 8. The integrated optical circuit of any one of the above Examples, wherein the shunt optical waveguide is mechanically supported by a clamping structure.

[0390] Example 9. The integrated optical circuit of any one of the above Examples, wherein when the optical switch is in an ON state more than 80% of optical power propagating in the first optical waveguide is coupled to the second optical waveguide.

[0391] Example 10. The integrated optical circuit of any one of the above Examples, wherein the optical switch further comprises at least one microelectromechanical systems (MEMS) actuator configured to actuated the shunt optical waveguide to optically couple a first end region thereof to the first bus optical waveguide and a second end region thereof to the second bus optical waveguide.

[0392] Example 11. The integrated optical circuit of Example 10, wherein the at least one MEMS actuator comprises a first electrostatic actuator configured to move the first end region of the shunt optical waveguide and a second electrostatic actuator configured to move the second end region of the shunt optical waveguide.

[0393] Example 12. The integrated optical circuit of any one of the above Examples, wherein an end of the first bus optical waveguide and an end of the second bus optical waveguide each comprise an optical port configured to transmit light to, or receive light from, an external optical waveguide or an external optical device.

[0394] Example 13. The integrated optical circuit of Example 12, wherein the external optical waveguide comprises an optical fiber and the optical port comprises a fiber-to-waveguide coupler.

[0395] Example 14. The integrated optical circuit of Example 13, wherein the fiber-to-waveguide coupler comprises a surface optical coupler.

[0396] Example 15. The integrated optical circuit of any one of the above Examples, wherein an end of the first bus optical waveguide comprises an optical port and other end of the first bus optical waveguide is optically coupled to an integrated optical device on the first waveguide layer, or an integrated optical device on the second waveguide layer.

[0397] Example 16. The integrated optical circuit of any one of the above Examples, wherein both ends of the first bus optical waveguide each comprise an optical port.

[0398] Example 17. The integrated optical circuit of any one of the Examples 17 and 18, further comprising one or more inter-layer optical couplers configured to optically couple one or both ends of the second bus optical waveguide to one or more optical ports formed on the first waveguide layer.

[0399] Example 18. The integrated optical circuit of any one of the above Examples, wherein both ends of the second bus optical waveguide each comprise an optical port.

[0400] Example 19. The integrated optical circuit of any one of the above Examples, wherein an end of the second bus optical waveguide comprises an optical port and other end of the second bus optical waveguide is optically coupled to an integrated optical device on the second waveguide layer or an integrated optical device on the first waveguide layer via an inter-layer optical coupler.

[0401] Example 20. The integrated optical of any one of the Examples 18 and 19, further comprising one or more inter-layer optical couplers configured to optically couple one or both ends of the first optical waveguide to one or more optical ports formed on the second waveguide layer.

[0402] Example 21. The integrated optical circuit of any one of Examples 15-20, wherein the optical port or the one or more optical ports comprise a fiber-to-waveguide coupler.

[0403] Example 22. The integrated optical circuit of any one of Examples above, further comprising a first alignment structure in the first waveguide layer or on the substrate and a second alignment structure in the second waveguide layer, the first alignment structure physically or optically aligned with respect to the second alignment structure.

[0404] Example 23. The integrated optical circuit of Example 22, wherein the first alignment structure comprises a first portion of a loop-back waveguide structure and the second alignment structure comprises a second portion of the loop-back waveguide structure.

[0405] Example 24. The integrated optical circuit of Example 23, wherein the first portion of a loop-back waveguide structure comprises two optically isolated waveguide sections and the second portion of the loop-back waveguide structure comprises a loop-back waveguide section configured to be optically coupled to the two optically isolated waveguide sections via two inter-layer optical couplers.

[0406] Example 25. The integrated optical circuit of Example 22, wherein the first and second alignment structures comprise a matched pair of self-alignment structures configured to be mechanically engaged with each other.

[0407] Example 26. The integrated optical circuit of Example 25, wherein the matched pair of self-alignment structures comprise a protrusion and a matching hole or opening.

[0408] Example 27. The integrated optical circuit of Example 26, wherein the protrusion has a semispherical, a cylindrical, or a rectangular shape, and the hole or opening comprises a V-groove, a cylindrical hole, or a rectangular hole.

[0409] Example 28. The integrated optical circuit of any one of the above Examples, wherein the first and second alignment structures comprise a pair of alignment marks each formed in one of the first or second waveguide layers.

Example Embodiment IX

[0410] Example 1. A method of fabricating an integrated optical circuit switching (OCS) device having at least one optical switching cell, the method comprising:

fabricating a first wafer comprising:

lithographically patterning to form a first bus optical waveguide extending within a first waveguide layer on a front side of a first substrate, and

forming on the first substrate an optical switch structure comprising a shunt optical waveguide at least partly fixedly buried in a sacrificial material;

fabricating a second wafer comprising:

lithographically patterning to form a second optical bus waveguide extending within a second waveguide layer on a front side of a second substrate;

forming a plurality of mechanical stoppers each having a first portion formed on the first substrate and a second portion formed on the second substrate;

selectively removing the sacrificial material to release the shunt optical waveguide; and

bonding the second wafer to the first wafer by contacting at least the first portions of the mechanical stoppers to corresponding second portions of the mechanical stoppers such that the shunt optical waveguide is configured to moveably optically couple the first bus optical waveguide and the second bus optical waveguide upon activation to redirect light between the first and second bus optical waveguides.

[0411] Example 2. The method of any one of the above Examples, wherein forming the optical switch structure comprises forming a microelectromechanical system (MEMS) actuator configured to activate the shunt optical waveguide.

[0412] Example 3. The method of any one of the above Examples, wherein bonding the second wafer to the first wafer comprises aligning the first wafer with respect to the second wafer such that an end portion of the shunt optical waveguide is substantially parallel to the second optical waveguide.

[0413] Example 4. The method of any one of the above Examples, wherein the first wafer comprises a first portion of an alignment structure, the second wafer comprises a second portion of the alignment structure, and aligning the second wafer with respect to the first wafer comprises aligning the second portion of the alignment structure to the first portion of the alignment structure.

[0414] Example 5. The method of Example 4, wherein the first portion of the alignment structure comprises a pair of optically isolated waveguides and the second portion of the alignment structure comprises a loop back waveguide section configured to optically couple the pair of optically isolated waveguides when the first and second wafers are substantially aligned.

[0415] Example 6. The method of Example 5, wherein the alignment structure further comprises inter-layer optical couplers configured to couple light between the pair of optically isolated waveguides and the loop back waveguide section.

[0416] Example 7. The method of Example 6, wherein the inter-layer optical couplers comprise grating couplers.

[0417] Example 8. The method of Example 6, wherein the inter-layer optical couplers comprise tapered optical waveguides.

[0418] Example 9. The method of Example 4, wherein aligning the second wafer with respect to the first wafer comprises aligning the second wafer with respect to the first wafer in a first direction.

[0419] Example 10. The method of Example 9, wherein aligning the second wafer with respect to the first wafer further comprises aligning the second wafer with respect to the first wafer in a second direction.

[0420] Example 11. The method of Example 10, wherein the first wafer further comprises a first portion of a second alignment structure, the second wafer comprises a second portion of the second alignment structure, and aligning the second wafer with respect to the first wafer in the second direction comprises aligning the second portion of the second alignment structure to the first portion of the second alignment structure.

[0421] Example 12. The method of Example 10, wherein the first direction is substantially perpendicular to the second direction.

[0422] Example 13. The method of Example 4, wherein one of the first and second portions of the alignment structure comprises a plurality of protrusions and the other one comprises a plurality of openings configured to receive respective protrusions.

[0423] Example 14. The method of Example 13, wherein bonding the second wafer to the first wafer further comprises positioning the first and second wafers such that individual protrusions of the plurality of alignment protrusions are inserted into or are mechanically engaged with respective individual openings of the plurality of openings.

[0424] Example 15. The method of Example 13, wherein an individual protrusion of the plurality of protrusions comprises a semi-sphere or a pillar having circular or rectangular cross-section.

[0425] Example 16. The method of Example 13, wherein an individual protrusion of the plurality of protrusions comprises a polymeric material.

[0426] Example 17. The method of Example 13, wherein an individual opening of the plurality of openings comprises a v-groove, an etched pyramid, or an etched cuboid.

[0427] Example 18. The method of Example 4, wherein the first portion of the alignment structure comprises a first plurality of openings and the second portion of the alignment structure comprises a second plurality of openings.

[0428] Example 19. The method of Example 18, wherein first and second pluralities of alignment openings comprise one or both of etched pyramids and v-grooves.

[0429] Example 20. The method of Example 19, wherein bonding the second wafer to the first wafer further comprises providing a plurality of microbeads between the first and second wafers and positioning the first and second wafers such that individual microbeads provide mechanical linkage between individual openings of the first plurality of alignment openings and the respective individual openings of the second plurality of openings.

[0430] Example 21. The method of any one of the above Examples, wherein bonding the second wafer to the first wafer comprises bonding a first mechanical stopper to a second mechanical stopper.

[0431] Example 22. The method of any one of the above Examples, wherein bonding the second substrate to the first substrate comprises bonding a first bonding pad to a second bonding pad.

[0432] Example 23. The method of Example 2, wherein selectively removing the sacrificial material comprises removing the sacrificial material from the microelectromechanical structure to release a MEMS actuator.

Example Embodiment X

Example 1. An optical switching cell, comprising:

a first waveguide layer having formed therein a first bus optical waveguide;

a second waveguide layer having formed therein a second bus optical waveguide;

an optical switch comprising a shunt optical waveguide disposed in a vertical gap between the first and second bus optical waveguide layers and configured to moveably couple the first bus optical waveguide and the second bus optical waveguide upon activation; and

one or more microelectromechanical (MEMS) actuators configured to, upon actuation, mechanically move one or both end regions of the shunt optical waveguide

to cause the first bus optical waveguide to be optically coupled with the second bus optical waveguide.

[0433] Example 2. The optical switching cell of any one of the above Examples, wherein the one or more MEMS actuators comprise a first MEMS actuator configured to move a first end region of the shunt optical waveguide toward the first bus optical waveguide to optically couple the first end region to the first bus optical waveguide, and a second MEMS actuator configured to move a second end region of the shunt optical waveguide toward the second bus optical waveguide to optically couple the second end region to the second bus optical waveguide.

[0434] Example 3. The optical switching cell of any one of the above Examples, wherein the first MEMS actuator comprises a first electrostatic actuator.

[0435] Example 4. The optical switching cell of Example 2, wherein the first electrostatic actuator comprises a first electrode mechanically coupled to the shunt optical waveguide and a second electrode formed on the first waveguide layer.

[0436] Example 5. The optical switching cell of Example 4, wherein the first MEMS actuator is actuated by generating an electric potential difference between the first and second electrodes.

[0437] Example 6. The optical switching cell of any one of the above Examples, wherein the second MEMS actuator comprises a seesaw actuator.

[0438] Example 7. The optical switching cell of Example 6, wherein the seesaw actuator comprises a second electrostatic actuator and a lever beam rotationally connected to the substrate via torsion joints.

[0439] Example 8. The optical switching cell of Example 7, wherein the second electrostatic actuator comprises a first electrode formed on a first end of the lever beam and a second electrode formed on the first waveguide layer.

[0440] Example 9. The optical switching cell of Example 8, wherein the second MEMS actuator is actuated by generating an electric potential difference between the first and second electrodes.

[0441] Example 10. The optical switching cell of Example 8, wherein upon actuation the first end of the lever beam moves toward the first substrate causing the second

end of the lever beam to move away from the substrate causing the second end region of the shunt optical waveguide to move toward the second bus optical waveguide.

Example Embodiment XI

[0442] Example 1. An integrated optical circuit comprising:

a first plurality of bus optical waveguides formed over a substrate and terminating with a first plurality of optical ports;

a second plurality of bus optical waveguides formed over the substrate and terminating with a second plurality of optical ports;

a plurality of optical switches comprising a plurality of shunt optical waveguides configured to redirect light between individual optical bus waveguides of the first plurality of bus optical waveguides to the individual optical bus waveguides of the second plurality of bus optical waveguides, upon being activated by activation signals; and

a plurality of sensors disposed on the substrate and configured to generate a plurality of sensor signals indicating ON and OFF states of the plurality of optical switches.

[0443] Example 2. The integrated optical circuit of Example 1, wherein the plurality of sensors comprises capacitive sensors integrated with the plurality of optical switches, and wherein a sensor signal of the plurality of sensor signals indicates activation of one or both ends of an individual shunt waveguide of the plurality of shunt optical waveguides.

[0444] Example 3. The integrated optical circuit of Example 1, wherein the plurality of sensors comprises a first plurality of photodetectors optically coupled to the first plurality of bus optical waveguides, and a second plurality of photodetectors optically coupled to the second plurality of bus optical waveguides.

[0445] Example 4. The integrated optical circuit of Example 3, wherein the first plurality of photodetectors is optically coupled to the first plurality of bus optical

waveguides at positions between the first plurality of optical ports and the plurality of shunt optical waveguides.

[0446] Example 5. The integrated optical circuit of Example 3, wherein the plurality of sensor signals received from one or both the first and second pluralities of photodetectors indicate an amount of light coupled between the first and second pluralities of bus optical waveguides by the plurality of optical switches.

[0447] Example 6. The integrated optical circuit of Example 3, wherein the plurality of sensors further comprises a third plurality of photodetectors configured to receive light transmitted through the first plurality of bus optical waveguides via a plurality of waveguide ends opposite the first plurality of optical ports.

[0448] Example 7. The integrated optical circuit of Example 6, wherein the plurality of sensor signals received from the third plurality of photodetectors indicate an amount of light received from the first plurality of optical ports.

[0449] Example 8. The integrated optical circuit of Example 6, wherein the plurality of sensors further comprises a fourth plurality of photodetectors configured to receive light transmitted through the second plurality of bus optical waveguides via a plurality of waveguide ends opposite the second plurality of optical ports.

[0450] Example 9. The integrated optical circuit of Example 8, wherein the plurality of sensor signals received from the fourth plurality of photodetectors indicate an amount of light received from the second plurality of optical ports.

[0451] Example 10. The integrated optical circuit of Example 4, wherein the first and second plurality of photodetectors are evanescently coupled to the first and second pluralities of bus optical waveguides, respectively, by tap optical waveguides.

[0452] Example 11. The integrated optical circuit of Example 10, wherein the tap optical waveguides are configured to couple less than 1% of light propagating in individual ones of first and second pluralities of bus optical waveguides to individual ones of the of the first and second pluralities of the photodetectors, respectively.

[0453] Example 12. The integrated optical circuit of Example 4, wherein the first plurality of photodetectors is monolithically fabricated on the substrate.

[0454] Example 13. The integrated optical circuit of Example 12, wherein the first plurality of photodetectors is at least partially co-fabricated with the first plurality of bus optical waveguides.

[0455] Example 14. The integrated optical circuit of Example 12, wherein the first and second pluralities of photodetectors comprise regions of the first and second plurality of optical waveguides.

[0456] Example 15. The integrated optical circuit of Example 14, wherein the first and second pluralities of photodetectors comprise reverse biased PN junctions.

[0457] Example 16. The integrated optical circuit of Example 3, wherein the first and second pluralities of photodetectors comprise p-i-n photodetectors.

[0458] Example 17. The integrated optical circuit of Example 16, wherein an intrinsic region of a p-i-n photodetector of the first plurality of photodetectors comprises a portion of a bus optical waveguide of the first plurality of bus optical waveguides.

[0459] Example 18. The integrated optical circuit of Example 3, wherein a photodetector of the first and second pluralities of photodetectors are bonded to the substrate.

[0460] Example 19. The integrated optical circuit of Example 18, wherein a photodetector of the first and second pluralities of photodetectors comprises germanium or III-V semiconductor material.

[0461] Example 20. An optical system comprising the integrated optical circuit of Example 1, the optical system further comprising an electronic circuit configured to receive and process the plurality of sensor signals to determine the ON and OFF states of the plurality of optical switches.

[0462] Example 21. The optical system of Example 20, wherein the electronic circuit is further configured to receive indications of the activation signals and generate an alert signal indicative of malfunctioning or failure of an optical switch of the plurality optical switches.

[0463] Example 22. An optical system comprising the integrated optical circuit of Example 8, the optical system further comprising an electronic circuit configured to receive a first sensor signal from a first photodetector of the second pluralities of photodetectors and a second sensor signal from a second photodetector of the third pluralities

of photodetectors and determine one or both and efficiency, and the ON and OFF states of an optical switch of the plurality of optical switches.

[0464] Example 23. An optical system comprising the integrated optical circuit of Example 8, the optical system further comprising an electronic circuit configured to: receive indications of the activation signals provided to the plurality of optical switches,

determine a position of a failed optical switch with respect to first and second pluralities of bus optical waveguides using the indications of activation signals and sensor signals received from the third and fourth pluralities of the photodetectors,

generate an alert signal indicating the position of the failed optical switch.

[0465] Example 24. The integrated optical circuit of Example 1, wherein the plurality of shunt optical waveguides is configured to be optically isolated from the first and second plurality of bus optical waveguides when they are in the OFF state, and to optically couple individual bus optical waveguides of the first plurality of bus optical waveguides to individual bus optical waveguides of the second plurality of bus optical waveguides, when they are in the ON state.

[0466] Example 25. The integrated optical circuit of Example 1, further comprising a first waveguide layer formed on the substrate, the first waveguide layer having formed therein the first plurality of bus optical waveguides and the first plurality of optical ports, and a second waveguide layer having formed therein the second plurality of bus optical waveguides, wherein the first and second waveguide layers are vertically separated.

[0467] Example 26. The integrated optical circuit of Example 25, wherein a shunt optical waveguide of the plurality of shunt optical waveguide is disposed in a gap vertically between a first bus optical waveguide of the first plurality of bus optical waveguides and a second bus optical waveguide of the second plurality of bus optical waveguides and configured to moveably optically couple the first bus optical waveguide and the second bus optical waveguide upon activation to redirect light between the first and second bus optical waveguides.

[0468] Example 27. The integrated optical circuit of Example 26, further comprising a plurality of vertical vias serving as mechanical anchors and electrical connections between the first and second waveguide layers to fixedly suspend the second waveguide layer

above the first waveguide layer, the plurality of vertical vias formed of a material that is etch-selective to a sacrificial material removed from the gap during fabrication.

[0469] Example 28. The integrated optical circuit of Example 26, further comprising an inter-layer optical coupler configured to optically couple the second bus optical waveguide to an optical port of the first plurality of optical ports.

[0470] Example 29. The integrated optical circuit of Example 1, further comprising:

[0471] a fixed waveguide layer fixed on the substrate, the fixed waveguide layer comprising the first and second pluralities of bus optical waveguides; and

[0472] a suspended waveguide layer suspended over the fixed waveguide layer, the suspended waveguide layer vertically separated from the waveguide layer and mechanically supported by a conductive clamping structure; the suspended waveguide layer comprising the plurality of shunt optical waveguides.

[0473] Example 30. The integrated optical circuit of Example 29, wherein the conductive clamping structure clamps a longitudinal region of the shunt optical waveguides between respective end regions of the shunt optical waveguides, thereby defining a vertical distance between the fixed waveguide layer and the suspended waveguide layer.

[0474] Example 31. The integrated optical circuit of Example 30, wherein the conductive clamping structure comprises lithographically defined metallic pillars formed over the fixed waveguide layer and vertically extending through the suspended waveguide layer.

[0475] Example 32. The integrated optical circuit of Example 31, wherein a space between the fixed waveguide layer and the suspended waveguide layer is substantially free of material other than the conductive clamping structure.

[0476] Example 33. The integrated optical circuit of Example 31, wherein the conductive clamping structure is not electrically connected to circuitry.

[0477] Example 34. The integrated optical circuit of any one of Examples 1-33, wherein an optical switch of the plurality of optical switches comprises at least one microelectromechanical systems (MEMS) actuator configured to activate a corresponding shunt optical waveguide to optically couple a first end region thereof to a first bus optical waveguide of the first plurality of bus optical waveguides and a second end region thereof to

a second bus optical waveguide of the second plurality of bus optical waveguides, upon receiving an activation signal.

[0478] Example 35. An integrated optical circuit comprising:
a first waveguide layer formed on a substrate, the first waveguide layer having formed therein a first bus optical waveguide terminating with a first optical port;
a second waveguide layer vertically separated from the first waveguide layer, the second waveguide layer having formed therein a second bus optical waveguide terminating with a second optical port;
an microelectromechanical systems optical switch comprising a shunt optical waveguide disposed in a gap vertically between the first and second bus optical waveguides and configured to moveably optically couple the first bus optical waveguide and the second bus optical waveguide upon activation by an activation signal to redirect light between the first and second bus optical waveguides; and
at least one sensor disposed over the substrate and configured to generate a sensor signal indicating an ON or OFF state of the optical switch.

[0479] Example 36. The integrated optical circuit of Example 35, wherein the at least one sensor comprises a capacitive sensor integrated with the optical switch and the sensor signal indicates activation of one or both ends of the shunt waveguide.

[0480] Example 37. The integrated optical circuit of Example 35, wherein the at least one sensor comprises a first photodetector optically coupled to the first bus optical waveguide at a position between the first optical port and the shunt optical waveguide, and a second photodetector optically coupled to the second bus optical waveguide at a position between the second optical port and the shunt optical waveguide.

[0481] Example 38. The integrated optical circuit of Example 37, wherein the sensor signal indicates an amount of light coupled between the first and second bus optical waveguides.

[0482] Example 39. The integrated optical circuit of Example 37, wherein the first and second photodetectors are evanescently coupled to the first and second bus optical waveguides by first and second tap optical waveguides, respectively.

[0483] Example 40. The integrated optical circuit of Example 39, wherein first and second tap optical waveguides are configured to couple less than 1% of light

propagating in the first and second bus optical waveguides to the first and second photodetectors, respectively.

[0484] Example 41. The integrated optical circuit of Example 37, wherein the first and second photodetectors are monolithically on the first and second waveguide layers, respectively.

[0485] Example 42. The integrated optical circuit of Example 37, wherein the first and second photodetectors comprise regions of the first and second of optical waveguides, respectively.

[0486] Example 43. The integrated optical circuit of Example 41, wherein the first and second photodetectors comprise reverse biased PN junctions formed on opposite sides of the first and second optical waveguides, respectively.

[0487] Example 44. The integrated optical circuit of Example 37, wherein the first and second photodetectors comprise p-i-n photodetectors.

[0488] Example 45. The integrated optical circuit of Example 37, wherein the first and second photodetectors are bonded to the first and second waveguide layers, respectively.

[0489] Example 46. The integrated optical circuit of Example 45, wherein the first and second photodetectors comprise III-V semiconductor material.

[0490] Example 47. The integrated optical circuit of Example 35, further comprising a plurality of vertical vias serving as mechanical anchors and electrical connections between the first and second waveguide layers to fixedly suspend the second waveguide layer above the first waveguide layer, the plurality of vertical vias formed of a material that is etch-selective to a sacrificial material removed from the gap during fabrication.

[0491] Example 48. An optical system comprising the integrated optical circuit of Example 35, the optical system further comprising an electronic circuit configured to receive the sensor signal.

[0492] Example 49. The optical system of Example 48, further configured to receive the activation signal and generate an alert signal indicative of malfunctioning of the first or second optical switch.

[0493] Example 50. The integrated optical circuit of Example 48, wherein the shunt optical waveguide is configured to be optically isolated from the first and second bus

optical waveguides when the optical switch is in an OFF state, and to optically couple the first and second bus optical waveguides when the optical switch is in an ON state.

[0494] Example 51. The integrated optical circuit of Example 35, wherein the optical switch further comprises at least one microelectromechanical system (MEMS) actuator configured to activate the shunt optical waveguide to optically couple a first end region thereof to the first bus optical waveguide and a second end region thereof to the second bus optical waveguide.

[0495] Example 52. The integrated optical circuit of any one of Examples 35-51, wherein the optical switch comprises a MEMS optical switch.

[0496] Example 53. The integrated optical circuit of any one of Examples 1-33, wherein an optical switch of the plurality of optical switches comprises a MEMS optical switch.

[0497] Example 54. The integrated optical circuit of Examples 53, wherein the MEMS optical switch comprises a piezoelectric MEMS switch.

[0498] Example 55. The integrated optical circuit of Examples 51, wherein the MEMS actuator comprises a piezoelectric actuator.

[0499] Example 56. The integrated optical circuit of Example 34, wherein the optical switch of the plurality of optical switches comprises a MEMS optical switch.

[0500] Example 57. The integrated optical circuit of Example 56, wherein the MEMS optical switch comprises a piezoelectric MEMS switch.

[0501] Example 58. The integrated optical circuit of Example 34, wherein the MEMS actuator comprises a piezoelectric actuator.

Example Embodiment XII

[0502] Example 1. An integrated optical circuit comprising:
a first bus optical waveguide formed over a substrate;
a second bus optical waveguide formed over the substrate;
a recovery optical waveguide formed over the substrate;
a primary optical switch comprising a first shunt optical waveguide configured to moveably optically couple the first bus optical waveguide and the second bus optical

waveguide upon activation by a first activation signal to redirect light between the first and second bus optical waveguides;

a first recovery optical switch comprising a second shunt optical waveguide configured to moveably optically couple the first bus optical waveguide and the recovery optical waveguide upon being activated by a second activation signal to redirect light between the first bus optical waveguide and the recovery optical waveguide; and

a second recovery optical switch comprising a third shunt optical waveguide configured to moveably optically couple the second bus optical waveguide and the recovery optical waveguide upon being activated by a third activation signal to redirect light between the second bus optical waveguide and the recovery optical waveguide,

wherein the recovery optical waveguide is configured to couple the first and second bus optical waveguides when the second and third optical switches are activated.

[0503] Example 2. The integrated optical circuit of Example 1, wherein the first bus optical waveguide is optically coupled to a first optical port of the integrated optical circuit and the second bus optical waveguide is optically coupled to a second optical port of the integrated optical circuit such that upon being activated, the primary optical switch optically couples the first and second bus optical waveguides.

[0504] Example 3. The integrated optical circuit of Example 2, further comprising a first photodetector configured to receive light from the first bus optical waveguide and to generate a first detector signal indicative of an amount light received from the first optical port via the first bus optical waveguide.

[0505] Example 4. The integrated optical circuit of Example 3, wherein the first photodetector is configured to receive light from an end of the first bus optical waveguide opposite the first optical port.

[0506] Example 5. The integrated optical circuit of Example 3, wherein the first photodetector comprises a p-i-n photodetector.

[0507] Example 6. The integrated optical circuit of Example 5, wherein an intrinsic region of the first photodetector comprise a portion of the first bus optical waveguide.

[0508] Example 7. The integrated optical circuit of Example 3, wherein the first photodetector comprises germanium or III-V semiconductor material.

[0509] Example 8. The integrated optical circuit of Example 3, further comprising a second photodetector configured to receive light from the recovery optical waveguide and to generate a second detector signal indicative of an amount light received from the first optical port via the recovery optical waveguide.

[0510] Example 9. An optical system comprising the integrated optical circuit of Example 3, the optical system further comprising an electronic circuit configured to receive the first detector signal and use the first detector signal to determine an ON or OFF state of the primary optical switch based at least in part on the first detector signal.

[0511] Example 10. The optical system of Example 9, further configured to:
receive an indication of the first activation signal provided to the primary optical switch; and

generate an alert signal in response to receiving the indication of the first activation signal and determining that the primary optical switch is in the OFF state.

[0512] Example 11. The optical system of Example 9, further configured to:
receive an indication of the first activation signal provided to the primary optical switch; and

in response to receiving the indication of the first activation signal and determining that the primary optical switch in the OFF state, provide the second and third activation signals to the first and second recovery optical switches, respectively, to activate the first and second recovery optical switches and to optically couple the first and second bus optical waveguides via the recovery optical waveguide.

[0513] Example 12. The optical system of Example 11, wherein the integrated optical circuit further comprises a second photodetector configured to receive light from the recovery optical waveguide and to generate a second detector signal indicative of an amount light received from the first optical port and the optical system is further configured to receive the second detector signal and to determine an ON or OFF state of the first and second recovery optical switches.

[0514] Example 13. The integrated optical circuit of Example 1, comprising:

a first waveguide layer formed on the substrate, the first waveguide layer having formed therein the first bus optical waveguide and a first section of the recovery optical waveguide; and

a second waveguide layer vertically separated from the first waveguide layer, the second waveguide layer having formed therein the second bus optical waveguide and a second section of the recovery optical waveguide,

wherein the first shunt optical waveguide is disposed in a gap vertically between the first and second bus optical waveguides, the second shunt optical waveguide is disposed in a gap vertically between the first bus optical waveguide and the first section of the recovery optical waveguide, and the third shunt optical waveguide is disposed in a gap vertically between the second bus optical waveguide and the second section of the recovery optical waveguide, and

wherein the first and second sections of the recovery optical waveguide are optically coupled via a first inter-layer optical coupler and are configured to form the recovery optical waveguide.

[0515] Example 14. The integrated optical circuit of Example 13, wherein the first bus optical waveguide is optically coupled to a first optical port formed on the second waveguide layer and the second bus optical waveguide is optically coupled to a second optical port formed on the second waveguide layer.

[0516] Example 15. The integrated optical circuit of Example 14, further comprising a first photodetector fabricated on a first waveguide layer and a second photodetector fabricated on the second waveguide layer, where the first and second photodetectors are configured to receive light from the first and second bus optical waveguides, respectively.

[0517] Example 16. The integrated optical circuit of Example 15, further comprising a third photodetector fabricated on a first waveguide layer and a fourth photodetector fabricated on the second waveguide layer, where the third and fourth photodetectors are configured to receive light from the first and second sections of the recovery optical waveguide, respectively.

[0518] Example 17. The integrated optical circuit of Example 14, wherein the first bus optical waveguide is optically coupled to the first optical port a second inter-layer optical coupler.

[0519] Example 18. The integrated optical circuit of Example 17, wherein the first and second inter-layer optical couplers each comprise a first portion formed on the first waveguide layer and a second portion formed on the second waveguide layer.

[0520] Example 19. The integrated optical circuit of Example 1, comprising:
a fixed waveguide layer fixed on the substrate, the fixed waveguide layer comprising the first and second bus optical waveguides and the recovery bus optical waveguide; and

a suspended waveguide layer suspended over the fixed waveguide layer, the suspended waveguide layer vertically separated from the waveguide layer and mechanically supported by a conductive clamping structure; the suspended waveguide layer comprising the first, second, and third shunt optical waveguides.

[0521] Example 20. The integrated optical circuit of Example 19, wherein the conductive clamping structure clamps a longitudinal region of the first, second, and third shunt optical waveguides between respective end regions of the first, second, and third shunt optical waveguides, thereby defining a vertical distance between the fixed waveguide layer and the suspended waveguide layer.

[0522] Example 21. The integrated optical circuit of Example 20, wherein the conductive clamping structure comprises a lithographically defined metallic pillar formed over the fixed waveguide layer and vertically extending through the suspended waveguide layer.

[0523] Example 22. The integrated optical circuit of Example 21, wherein the metallic pillar is formed of aluminum or copper.

[0524] Example 23. The integrated optical circuit of Example 21, wherein the conductive clamping structure further comprises planar metallic layers connected to opposing ends of the metallic pillar.

[0525] Example 24. The integrated optical circuit of Example 21, wherein a space between the fixed waveguide layer and the suspended waveguide layer is substantially free of material other than the conductive clamping structure.

[0526] Example 25. The integrated optical circuit of Example 21, wherein the conductive clamping structure is not electrically connected to circuitry.

[0527] Example 26. The integrated optical circuit of Example 19, wherein the substrate comprises a silicon wafer having a silicon dioxide layer having the fixed waveguide layer formed thereover.

[0528] Example 27. The integrated optical circuit of Example 19, wherein the first bus optical waveguide comprises a silicon nitride layer that has been deposited over a sacrificial material that has been removed.

[0529] Example 28. The integrated optical circuit of Example 19, wherein the first bus optical waveguide comprises monocrystalline silicon transferred from a silicon-on - insulator (SOI) substrate by flip-chip bonding.

[0530] Example 29. The integrated optical circuit of any one of the Examples 1-28, wherein each of the primary optical switch, first recovery optical switch and second recovery optical switch further comprises at least one microelectromechanical systems (MEMS) actuator configured to activate the first shunt optical waveguide to optically couple a first end region thereof to the first bus optical waveguide and a second end region thereof to the second bus optical waveguide.

[0531] Example 30. The integrated optical circuit of any one of the Examples 1-28, wherein each of the primary optical switch, first recovery optical switch and second recovery optical switch comprises a microelectromechanical systems (MEMS) optical switch.

[0532] Example 31. The integrated optical circuit of Example 30, wherein the MEMS optical switch comprises a piezoelectric MEMS switch.

[0533] Example 32. The integrated optical circuit of Example 29, wherein the MEMS actuator comprises a piezoelectric actuator.

Example Embodiment XIII

[0534] Example 1. An integrated optical circuit comprising:
a first waveguide layer formed on a substrate, the first waveguide layer having formed therein a first bus optical waveguide and a first recovery optical waveguide section;

a second waveguide layer vertically separated from the first waveguide layer, the second waveguide layer having formed therein a second bus optical waveguide and a second recovery optical waveguide section;

a primary optical switch comprising a first shunt optical waveguide disposed in a gap vertically between the first and second bus optical waveguides and configured to moveably optically couple the first bus optical waveguide and the second bus optical waveguide upon activation by a first activation signal to redirect light between the first and second bus optical waveguides; and

a first recovery optical switch comprising a second shunt optical waveguide disposed in a gap vertically between the first bus optical waveguide and the second recovery optical waveguide section and configured to moveably optically couple the first bus optical waveguide and the second recovery optical waveguide section upon being activated by a second activation signal to redirect light between the first bus optical waveguide and the second recovery optical waveguide section;

a second recovery optical switch comprising a third shunt optical waveguide disposed in a gap vertically between the second bus optical waveguide and the first recovery optical waveguide section and configured to moveably optically couple the second bus optical waveguide and the first recovery optical waveguide section upon being activated by a second activation signal to redirect light between the second bus optical waveguide and the first recovery optical waveguide section;

wherein the first and second recovery optical waveguide sections optically are coupled via a first inter-layer optical coupler and are configured to form a recovery optical path between the first and second waveguides, when the first and second recovery optical switches are activated.

[0535] Example 2. The integrated optical circuit of Example 1, wherein the first bus optical waveguide is optically coupled to a first optical port of the integrated optical circuit and the second bus optical waveguide is optical coupled to a second optical port of the integrated optical circuit such that up on being activated the primary optical switch optically couples the first and second bus optical waveguides.

[0536] Example 3. The integrated optical circuit of Example 2, further comprising a first photodetector configured to receive light from the first bus optical

waveguide and to generate a first detector signal indicative of an amount light received from the first optical port and a second photodetector configured to receive light from the second bus optical waveguide and to generate a second detector signal indicative of an amount light received from the first optical port.

[0537] Example 4. The integrated optical circuit of Example 3, wherein the first photodetector receives light from an end of the first bus optical waveguide opposite the first optical port and the second photodetector receives light from an end of the second bus optical waveguide opposite the second optical port.

[0538] Example 5. The integrated optical circuit of Example 4, wherein the first photodetector is fabricated on the first waveguide layer and the second photodetector is fabricated on the second waveguide layer.

[0539] Example 6. The integrated optical circuit of Example 3, further comprising a third photodetector configured to receive light from the first recovery optical waveguide section and to generate a third detector signal indicative of an amount light received from the second recovery optical waveguide section and a fourth photodetector configured to receive light from the second recovery optical waveguide section and to generate a fourth detector signal indicative of an amount light received from the first recovery optical waveguide section.

[0540] Example 7. The integrated optical circuit of Example 6, wherein the third photodetector receives light from an end of the first recovery optical waveguide section opposite the first inter-layer optical coupler and the fourth photodetector receives light from an end of the second recovery optical waveguide section opposite the first inter-layer optical coupler.

[0541] Example 8. The integrated optical circuit of Example 7, wherein the third photodetector is fabricated on the first waveguide layer and the fourth photodetector is fabricated on the second waveguide layer.

[0542] Example 9. The integrated optical circuit of any one of Examples 6-8, wherein the first, second, third, and fourth photodetectors are monolithically fabricated on the substrate.

[0543] Example 10. The integrated optical circuit of any one of Examples 6-8, wherein the first, second, third, and fourth photodetectors are co-fabricated with the first or second bus optical waveguide.

[0544] Example 11. The integrated optical circuit of any one of Examples 6-10, wherein at least one of the first, second, third, and fourth photodetectors comprises a portion of the first optical waveguide.

[0545] Example 12. The integrated optical circuit of Example 11, wherein at least one of the first, second, third, and fourth photodetectors comprises a PN junction formed on opposite sides of respective bus optical waveguide.

[0546] Example 13. The integrated optical circuit of Example 12, wherein at least one of the first, second, third, and fourth photodetectors comprise a p-i-n photodetector.

[0547] Example 14. The integrated optical circuit of any one of Examples 6-8, wherein at least one of the first, second, third, and fourth photodetectors is bonded to the substrate.

[0548] Example 15. The integrated optical circuit of any one of Examples 6-8, wherein at least one of the first, second, third, and fourth photodetectors comprises germanium or III-V semiconductor material.

[0549] Example 16. An optical system comprising the integrated optical circuit of Example 6, the optical system further comprising an electronic circuit configured to receive the first or second detector signals and use one or both of the first and second detector signals to determine a state of the primary optical switch.

[0550] Example 17. The optical system of Example 16, further configured:
to receive the first activation signal provided to the primary optical switch; and
in response to receiving the first activation signal and determining that the primary optical switch in an OFF state, generate an alert signal.

[0551] Example 18. The optical system of Example 16, further configured to:
receive the first activation signal provided to the primary optical switch; and
in response to receiving the first activation signal and determining that the primary optical switch in an OFF state, activate the first and second recovery optical switches and establish the recovery optical path by providing the second and third activation signals to the first and second recovery optical switches, respectively.

[0552] Example 19. The optical system of Example 18, further configured to receive the third and fourth detector signals and use the third and fourth detector signals to determine the states of the third and fourth optical switches.

[0553] Example 20. The integrated optical circuit of Example 1, further comprising a plurality of vertical vias serving as mechanical anchors and electrical connections between the first and second waveguide layers to fixedly suspend the second waveguide layer above the first waveguide layer, the plurality of vertical vias formed of a material that is etch-selective to a sacrificial material removed from the gap during fabrication.

[0554] Example 21. The integrated optical circuit of any one of Examples 1-20, wherein each of the primary optical switch, the first recovery optical switch, and the second recovery optical switch further comprises at least one microelectromechanical systems (MEMS) actuator configured to activate the first, second, and third shunt optical waveguides.

[0555] Example 22. The integrated optical circuit of Example 1, wherein each of the primary optical switch, the first recovery optical switch, and the second recovery optical switch comprises a microelectromechanical systems (MEMS) optical switch.

[0556] Example 23. The integrated optical circuit of Example 22, wherein the MEMS optical switch comprises a piezoelectric MEMS switch.

[0557] Example 24. The integrated optical circuit of Example 21, wherein the MEMS actuator comprises a piezoelectric actuator.

Example Embodiment XIV

[0558] Example 1. An integrated optical circuit comprising:
a first plurality of optical waveguides longitudinally extending on a substrate and terminating near an edge of a substrate;
a first edge optical coupler formed on the substrate and configured to optically couple an optical fiber to a first optical waveguide of the first plurality of optical waveguides, the first edge optical coupler comprising a tapered waveguide longitudinally extending from an end of the first optical waveguide to the edge of the substrate, wherein a lateral width of the tapered waveguide decreases from the end of the first optical waveguide to the edge of the substrate, and wherein a region of the

substrate below the tapered waveguide is removed to form a slit under the tapered waveguide.

[0559] Example 2. The integrated optical circuit of Example 1, wherein the tapered waveguide is formed in a top cladding layer formed on the substrate, the top cladding layer comprising a first dielectric material.

[0560] Example 3. The integrated optical circuit of Example 2, wherein a bottom surface of the top cladding layer is exposed through the slit and where in a vertical distance between the tapered waveguide and the exposed bottom surface of the top cladding layer is less than two times a design wavelength of the tapered waveguide.

[0561] Example 4. The integrated optical circuit of Example 2, wherein the slit comprises air.

[0562] Example 5. The integrated optical circuit of Example 3, wherein the slit is filled with a second dielectric material.

[0563] Example 6. The integrated optical circuit of Example 3, further comprising a dielectric lining formed on the exposed bottom surface of the top cladding layer and side walls of the slit, the dielectric lining comprising a second dielectric material.

[0564] Example 7. The integrated optical circuit of any one of Examples 5 and 6, wherein optical absorption coefficients of the first and second dielectric materials is less than 0.01 cm^{-1} at the design wavelength of the tapered waveguide.

[0565] Example 8. The integrated optical circuit of Example 2, wherein the first plurality of optical waveguides is formed in the top cladding layer comprising a first dielectric, and wherein the slit is filled with a second dielectric material.

[0566] Example 9. The integrated optical circuit of any one of Examples 5-8, wherein the first dielectric material is different from the second dielectric material.

[0567] Example 10. The integrated optical circuit of Example 1, wherein the lateral width of the tapered waveguide decreases linearly from the end of the first optical waveguide to the edge of the substrate.

[0568] Example 11. The integrated optical circuit of Example 1, wherein the lateral width of the tapered waveguide decreases nonlinearly from the end of the first optical waveguide to the edge of the substrate.

[0569] Example 12. The integrated optical circuit of Example 1, wherein a first lateral width of the tapered waveguide near the edge of the substrate is at least 1.2 times smaller than a second lateral width of the tapered waveguide at end of the first optical waveguide.

[0570] Example 13. The integrated optical circuit of Example 12, wherein the second lateral width is substantially equal to a lateral width of the first optical waveguide.

[0571] Example 14. The integrated optical circuit of Example 1, wherein the slit is extended in a longitudinal direction substantially parallel to tapered waveguide.

[0572] Example 15. The integrated optical circuit of Example 14, wherein a length of the slit is greater than 30% of a length of the tapered waveguide.

[0573] Example 16. The integrated optical circuit of Example 12, wherein a lateral width of the slit is greater than the second lateral width of the tapered waveguide.

[0574] Example 17. The integrated optical circuit of Example 1, further comprising:

- a second plurality of optical waveguides fabricated over the substrate terminating with a second plurality of optical ports; and

- a plurality optical switches comprising shunt optical waveguides configured to redirect light between individual optical waveguides of the first plurality of optical waveguides to individual optical waveguides of the second plurality of optical waveguides, upon being activated by an activation signal.

[0575] Example 21. The integrated optical circuit of Examples 17, wherein each of the plurality of optical switch further comprises at least one microelectromechanical systems (MEMS) actuator configured to activate the shunt optical waveguide.

[0576] Example 22. The integrated optical circuit of Example 17, wherein the optical switch comprises a microelectromechanical systems (MEMS) optical switch.

[0577] Example 23. The integrated optical circuit of Example 21, wherein the MEMS actuator comprises a piezoelectric actuator.

[0578] Example 24. The integrated optical circuit of any one of examples 1-23, wherein the first edge optical coupler comprises a fiber-to-chip optical coupler.

Example Embodiment XV

[0579] Example 1. A edge coupler interposer comprising:
a first array of waveguide facets at first periodic positions along a lateral direction, a first longitudinal position and a common vertical position; and
second and third arrays of waveguide facets, at a second longitudinal position, wherein the second and third arrays of waveguide facets are vertically separated and form an array of vertically separated waveguide facet pairs at second periodic positions along the lateral direction,
wherein a first lateral pitch of the first array of waveguide facets is smaller than a second lateral pitch of the second array of waveguide facets;
wherein first and second waveguide facets of the first array of waveguide facets are optically coupled to different waveguide facets of a vertically separated waveguide facet pair of the array of vertically separated waveguide facet pairs, respectively.

[0580] Example 2. The edge coupler interposer of Example 1, wherein the first and second waveguide facets are nearest neighboring waveguide facets.

[0581] Example 3. The edge coupler interposer of Example 1, wherein the first lateral pitch of the first array of waveguide facets is at least two times smaller than the second lateral pitch of the second array of waveguide facets.

[0582] Example 4. The edge coupler interposer of Example 1, further comprising a plurality of optical waveguides extending in a longitudinal direction from the first longitudinal position to second longitudinal position and optically coupling the first array of waveguide facets to the second and third arrays of waveguide facets.

[0583] Example 5. The edge coupler interposer of Example 4, wherein first and second waveguides of the plurality of waveguides optically couple the first and second waveguide facets of the first array of waveguide facets to third and fourth waveguide facets of the vertically separated waveguide facet pair, respectively.

[0584] Example 6. The edge coupler interposer of Example 1, wherein the second longitudinal position is at least 0.1 millimeter greater than the first longitudinal position.

[0585] Example 7. The edge coupler interposer of Example 1, wherein the first array of waveguide facets are optically aligned with and coupled to waveguide facets of

an array of optical waveguides of a photonic integrated circuit (PIC) formed on a substrate, the optical waveguides terminating with the waveguide facets at an edge of the PIC at third periodic positions along the lateral direction and along a major surface of the substrate, wherein a third lateral pitch of the third periodic positions is substantially equal to the first lateral pitch of the first periodic positions.

[0586] Example 8. The edge coupler interposer of Example 1, wherein the first array of waveguide facets are optically aligned with and coupled to waveguide facets of a first array of bus optical waveguides of an integrated optical circuit switch (IOCS) formed on a substrate, the bus optical waveguides terminating with the waveguide facets at an edge of the IOCS at third periodic positions along the lateral direction and along a major surface of the substrate, wherein a third lateral pitch of the third periodic positions is substantially equal to the first lateral pitch of the first periodic positions, and wherein the IOCS comprises a second array of bus optical waveguides controllably optically coupled to the first array of bus optical waveguides by a plurality of microelectromechanical systems (MEMS) optical switches.

[0587] Example 9. The integrated optical circuit of any one of examples 1-8, wherein the edge coupler interposer comprises a fiber-to-chip interposer coupler.

Additional Considerations

[0588] As for additional details pertinent to the present invention, materials and manufacturing techniques may be employed as within the level of those with skill in the relevant art. The same may hold true with respect to method-based aspects of the invention in terms of additional acts commonly or logically employed. Also, it is contemplated that any optional feature of the inventive variations described may be set forth and claimed independently, or in combination with any one or more of the features described herein. Likewise, reference to a singular item, includes the possibility that there are plural of the same items present. More specifically, as used herein and in the appended claims, the singular forms "a," "and," "said," and "the" include plural referents unless the context clearly dictates otherwise. It is further noted that the claims may be drafted to exclude any optional element. As such, this statement is intended to serve as antecedent basis for use of such exclusive terminology as "solely," "only" and the like in connection with the recitation of claim elements, or use of a "negative" limitation. Unless defined otherwise herein, all technical and scientific

terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this invention belongs. The breadth of the present invention is not to be limited by the subject specification, but rather only by the plain meaning of the claim terms employed.

[0589] In the embodiments described above, apparatus, systems, and methods for sensing electrical overstress events are described in connection with particular embodiments. It will be understood, however, that the principles and advantages of the embodiments can be used for any other systems, apparatus, or methods with a need for sensing and/or protecting against electrical overstress events.

[0590] The principles and advantages described herein can be implemented in various apparatuses. Examples of such apparatuses can include, but are not limited to, consumer optical systems, optical communication systems, optical networks, RF/microwave photonic networks, quantum computing, photonic circuits, photonic systems, quantum communication, photonic sensing systems, microwave photonic systems, RF/Microwave over fiber communication, opto-electronic products, opto-electronic parts and systems, consumer electronic and opto-electronic products, electronic test equipment, optical test and measurement, micro-wave photonic test and measurement, sensor networks, optical sensor networks, optically connected computer systems, servers, and data bases, etc.

[0591] Unless the context clearly requires otherwise, throughout the description and the claims, the words “comprise,” “comprising,” “include,” “including,” and the like are to be construed in an inclusive sense, as opposed to an exclusive or exhaustive sense; that is to say, in the sense of “including, but not limited to.” The words “coupled” or “connected”, as generally used herein, refer to two or more elements that may be either directly connected, or connected by way of one or more intermediate elements. Additionally, the words “herein,” “above,” “below,” and words of similar import, when used in this application, shall refer to this application as a whole and not to any particular portions of this application. Where the context permits, words in the Detailed Description using the singular or plural number may also include the plural or singular number, respectively. The word “or” in reference to a list of two or more items, is intended to cover all of the following interpretations of the word: any of the items in the list, all of the items in the list, and any combination of the items in the list. All numerical values provided herein are intended to include similar values within a measurement error.

[0592] Moreover, conditional language used herein, such as, among others, “can,” “could,” “might,” “may,” “e.g.,” “for example,” “such as” and the like, unless specifically stated otherwise, or otherwise understood within the context as used, is generally intended to convey that certain embodiments include, while other embodiments do not include, certain features, elements and/or states.

[0593] The teachings of the inventions provided herein can be applied to other systems, not necessarily the systems described above. The elements and acts of the various embodiments described above can be combined to provide further embodiments. The acts of the methods discussed herein can be performed in any order as appropriate. Moreover, the acts of the methods discussed herein can be performed serially or in parallel, as appropriate.

[0594] While certain embodiments of the inventions have been described, these embodiments have been presented by way of example only, and are not intended to limit the scope of the disclosure. Indeed, the novel methods and systems described herein may be embodied in a variety of other forms. Furthermore, various omissions, substitutions and changes in the form of the methods and systems described herein may be made without departing from the spirit of the disclosure. The accompanying claims and their equivalents are intended to cover such forms or modifications as would fall within the scope and spirit of the disclosure. Accordingly, the scope of the present inventions is defined by reference to the claims.

WHAT IS CLAIMED IS :

1. An integrated optical circuit comprising:
 - a first waveguide layer formed on a substrate, the first waveguide layer having formed therein a first bus optical waveguide;
 - a second waveguide layer having formed therein a second bus optical waveguide;
 - an optical switch comprising a shunt optical waveguide disposed in a gap vertically between the first and second bus optical waveguides and configured to moveably optically couple the first bus optical waveguide and the second bus optical waveguide upon activation to redirect light between the first and second bus optical waveguides; and
 - a plurality of vertical vias serving as mechanical anchors and electrical connections between the first and second waveguide layers to fixedly suspend the second waveguide layer above the first waveguide layer, the plurality of vertical vias formed of a material that is etch-selective to a sacrificial material removed from the gap during fabrication.
2. The integrated optical circuit of Claim 1, wherein the shunt optical waveguide is configured to be optically isolated from the first and second bus optical waveguides when the optical switch is in an OFF state, and to optically couple the first and second bus optical waveguides when the optical switch is in an ON state.
3. The integrated optical circuit of Claim 1, wherein a thickness of the second waveguide layer is less than 800 microns.
4. The integrated optical circuit of Claim 1, wherein the optical switch further comprises at least one microelectromechanical systems (MEMS) actuator configured to activate the shunt optical waveguide to optically couple a first end region thereof to the first bus optical waveguide and a second end region thereof to the second bus optical waveguide.
5. The integrated optical circuit of Claim 1, further comprising an inter-layer optical coupler configured to optically couple an end of the first bus optical waveguide to an optical port formed on the second waveguide layer, or to optically couple an end of the second bus optical waveguide to an optical port formed on the first waveguide layer.

6. The integrated optical circuit of Claim 5, wherein the optical port comprises a fiber-to-waveguide optical coupler.

7. The integrated optical circuit of Claim 1, further comprising a first optical alignment structure in the first waveguide layer or on the substrate, and a second optical alignment structure in the second waveguide layer, the first optical alignment structure configured to be optically coupled to the second optical alignment structure to form a loop back waveguide structure.

8. The integrated optical circuit of Claim 1, wherein one or more of the plurality of vertical vias comprises a conductive via.

9. The integrated optical circuit of Claim 8, wherein the one or more of the plurality of vertical via comprises a dielectric region.

10. A method of fabricating an integrated optical circuit device, the method comprising:

fabricating a first wafer comprising:

lithographically patterning to form a first bus optical waveguide extending within a first waveguide layer on a front side of a first substrate, and

forming on the first substrate an optical switch structure comprising a shunt optical waveguide at least partly fixedly buried in a sacrificial material;

fabricating a second wafer comprising lithographically patterning to form a second bus optical waveguide extending within a second waveguide layer on a front side of a second substrate;

bonding the front side of the second wafer to the front side the first wafer;

removing the second substrate;

forming a plurality of vertical vias through the second waveguide layer and further through the sacrificial material, the plurality of vertical vias serving as mechanical anchors and electrical connections between the first and second waveguide layers; and

selectively removing the sacrificial material to release the shunt optical waveguide to configure the shunt optical waveguide to moveably optically couple the first bus optical waveguide and the second bus optical waveguide, upon activation, to redirect light between the first and second bus optical waveguides.

11. The method of Claim 10, wherein forming the optical switch structure comprises forming a microelectromechanical systems (MEMS) structure.

12. The method of Claim 11, wherein selectively removing the sacrificial material comprises removing the sacrificial material from the MEMS structure to release a MEMS actuator configured to activate the shunt optical waveguide.

13. The method of Claim 12, wherein the sacrificial material comprises a material that is etch-selective against materials of the MEMS actuator and the shunt optical waveguide.

14. The method of Claim 10, wherein bonding the second wafer to the first wafer comprises optically aligning the shunt optical waveguide to the second bus optical waveguide such that after removing the sacrificial material the shunt optical waveguide moveably optically couples the first bus optical waveguide and the second bus optical waveguide upon activation.

15. The method of Claim 10, wherein bonding the second wafer to the first wafer comprises optically coupling a pair of optically isolated waveguides formed on the first wafer and a loop back waveguide section formed on the second wafer.

16. The method of Claim 10, wherein forming the plurality of vertical vias comprises forming a conductive line vertically extending from the first wafer to the second wafer.

17. An integrated optical circuit device comprising:

- a first waveguide layer formed on a first substrate, first waveguide layer having formed therein a first bus optical waveguide;

- a second waveguide layer formed on a second substrate, the second waveguide layer having formed therein a second bus optical waveguide;

- an optical switch comprising a shunt optical waveguide disposed in a vertical gap between the first and second bus optical waveguide layers and configured to moveably optically couple the first bus optical waveguide and the second bus optical waveguide upon activation to redirect light between the first and second bus optical waveguides; and

- a plurality of mechanical stoppers vertically extending between the first and second substrates, wherein each mechanical stopper has a first mechanical stopper portion formed on the first substrate and a second mechanical stopper portion formed on the second substrate,

wherein the second substrate is bonded to the first substrate using the plurality of mechanical stoppers such that the first bus optical waveguide is vertically separated from the second bus optical waveguide by a distance defined by the mechanical stopper.

18. The integrated optical circuit device of Claim 17, wherein the plurality of mechanical stoppers are configured to establish a predefined vertical spacing between the first and second bus optical waveguides.

19. The integrated optical circuit device of Claim 17, wherein the first mechanical stopper portion is bonded to the second mechanical stopper portion.

20. The integrated optical circuit device of Claim 17, further comprising a first optical alignment structure in the first waveguide layer or on the first substrate and a second optical alignment structure in the second waveguide layer or on the second substrate, the first optical alignment structure configured to be optically coupled to the second optical alignment structure forming a loop back waveguide structure.

21. The integrated optical circuit device of Claim 20, wherein the optical switch is formed over a first region of the first substrate and the first optical alignment structure is formed in a second region of the first substrate, and wherein the first and second regions are non-overlapping.

22. The integrated optical circuit device of Claim 17, wherein the optical switch further comprises at least one microelectromechanical systems (MEMS) actuator configured to activate the shunt optical waveguide to optically couple a first end region thereof to the first bus optical waveguide and a second end region thereof to the second bus optical waveguide.

23. The integrated optical circuit device of Claim 17, wherein the shunt optical waveguide is mechanically connected to the first substrate by a clamping structure.

24. A method of fabricating an integrated optical circuit switching device having at least one optical switching cell, the method comprising:

fabricating a first wafer comprising:

lithographically patterning to form a first bus optical waveguide extending within a first waveguide layer on a front side of a first substrate, and

forming on the first substrate an optical switch structure comprising a shunt optical waveguide at least partly fixedly buried in a sacrificial material;

fabricating a second wafer comprising:

lithographically patterning to form a second bus optical waveguide extending within a second waveguide layer on a front side of a second substrate;

forming a plurality of mechanical stoppers each having a first portion formed on the first substrate and a second portion formed on the second substrate;

selectively removing the sacrificial material to release the shunt optical waveguide; and

bonding the second wafer to the first wafer by contacting at least the first portions of the mechanical stoppers to corresponding second portions of the mechanical stoppers such that the shunt optical waveguide is configured to moveably optically couple the first bus optical waveguide and the second bus optical waveguide, upon activation, to redirect light between the first and second bus optical waveguides.

25. The method of Claim 24, wherein forming the optical switch structure comprises forming a microelectromechanical structure.

26. The method of Claim 25, wherein selectively removing the sacrificial material comprises removing the sacrificial material from the microelectromechanical structure to release a MEMS actuator configured to activate the shunt optical waveguide.

27. The method of Claim 26, wherein the MEMS actuator comprises a lever beam configured to optically couple an end of the shunt optical waveguide to the second bus optical waveguide.

28. The method of Claim 24, wherein bonding the second wafer to the first wafer comprises optically aligning the shunt optical waveguide to the second bus optical waveguide such that after removing the sacrificial material, the shunt optical waveguide moveably optically couples the first bus optical waveguide and the second bus optical waveguide upon activation.

29. The method of Claim 28, wherein optically aligning the shunt optical waveguide to the second bus optical waveguide comprises optically coupling a first optical alignment structure formed on the first wafer to a second optical alignment structure formed on the second wafer based on a measured optical power transmission from a first portion of the first optical alignment structure to a second portion thereof, through the second optical alignment structure.

30. The method of Claim 24, wherein bonding the second wafer to the first wafer comprises bonding the first and second portions of the mechanical stoppers.