

SPOT-SIZE CONVERTER FOR COUPLING SINGLE-MODE FIBER TO SOI WAVEGUIDE

FIELD

[001] The present disclosure relates to integrated photonic waveguides and more particularly to photonic edge couplers or spot-size converters which provide mode conversion between waveguides supporting propagation modes of different dimensions and further provide efficient adiabatic coupling between the waveguides to achieve smaller device footprint, high-efficiency coupling, improved mechanical reliability, more simplified fabrication and packaging.

BACKGROUND

[002] Low loss coupling of light into and out of photonic chips is highly desired in reducing link budget of optical communication links.

[003] Existing solutions to achieve efficient coupling between a silicon waveguide and a single-mode fiber (SMF) include surface gratings and spot-size converters (SSC) such as inverse tapers, suspended edge couplers, and multi-layer edge couplers. However, existing solutions are unsatisfactory.

[004] Surface gratings have limited optical bandwidth, and they are polarization sensitive, thus limiting their use in wavelength-division multiplexing.

[005] Edge couplers comprising inverse tapers have broad optical bandwidth as its operation is based on mode overlap principle. However, modal expansion is limited by substrate leakage due to the proximity of the silicon substrate to buried oxide layer (BOX) of silicon-on-insulator (SOI) wafers. Even though a low coupling loss is achievable for fibers with small mode-field diameters (MFD), coupling loss substantially increases for standard single-mode fibers with larger MFD.

[006] Another class of edge couplers uses silicon oxide cladding material (hereinafter, "silicon oxide" and "oxide" may be used interchangeably) to define the coupling waveguide. This is achieved by isolating the silicon oxide coupling waveguide from the bulk cladding material via a series of etching steps. The resulting suspended

oxide waveguide provides isolation from the cladding material as well as the bulk substrate so that the substrate leakage is prevented. Besides, the width of the suspended oxide waveguide can be tailored to match the mode size of the waveguide to that of the input beam. The coupling interface is improved further by using an index-matching oil between the fiber and the cleaved chip facet by mitigating the oxide-air-oxide interface.

[007] However, the suspended nature of these edge couplers poses risks in terms of mechanical reliability, e.g., tip damage, collapse, especially during fiber packaging. Moreover, the use of index-matching oil and post UV-curing steps increase packaging complexity. Thus, there is a need for mechanically robust, oil-free spot-size converters to facilitate efficient coupling interface between standard single-mode fibers and silicon photonics chips.

[008] To improve mechanical reliability while preserving high-efficiency coupling with standard single-mode fibers, another class of edge couplers comprising multiple layers of higher-index waveguides with smaller feature sizes within a lower index cladding material has emerged. Such SSCs have the advantage of conventional edge couplers having the large optical bandwidth and lower polarization dependent loss compared to grating couplers while retaining mechanical rigidity due to lack of any suspended structure.

[009] These devices comprise a few layers of higher-index waveguides cladded with a lower-index material and are usually positioned on top of a routing waveguide. In these SSCs having multiple-layer waveguides, they are usually provided with three or more high-index waveguide layers, with materials comprising silicon oxynitride (SiON), silicon nitride (SiN), cladded with silicon dioxide (SiO₂) to couple light from a SMF with various MFD to various waveguiding materials such as SiN or SOI.

SUMMARY

[010] According to an aspect, a spot-size converter is provided which comprises:

a layered arrangement having a first section and an adjoining second section which are arranged in a light propagation direction which is to traverse the first section followed by the second section, the layered arrangement having a plurality of upper

layers and a lower layer, wherein each upper layer includes a plurality of auxiliary waveguides which include a plurality of inner auxiliary waveguides and a plurality of outer auxiliary waveguides, wherein the lower layer includes a silicon-on-insulator (SOI) waveguide which partially traverses the first section and fully traverses the second section, wherein a width of the SOI waveguide widens in the light propagation direction; and

a cladding covering the auxiliary waveguides and the SOI waveguide,

wherein within the first section, a width of each auxiliary waveguide widens in the light propagation direction, wherein within the second section, the width of each auxiliary waveguide is non-tapered and the outer auxiliary waveguides are arranged to converge towards each other.

[011] In some embodiments, within the first section, a spacing between the inner auxiliary waveguides taper in the light propagation direction, wherein within the second section, the spacing distance between the inner auxiliary waveguides is non-tapered.

[012] In some embodiments, within the first section and the second section, a spacing distance between one of the inner auxiliary waveguides and an adjacent one of the outer auxiliary waveguides tapers in the light propagation direction.

[013] In some embodiments, within the first section, a spacing distance between one of the inner auxiliary waveguides and an adjacent one of the outer auxiliary waveguides tapers in the light propagation direction, wherein within the second section, the spacing distance between the one of the inner auxiliary waveguides and the adjacent one of the outer auxiliary waveguides is non-tapered.

[014] In some embodiments, within the first section, a spacing distance between one of the inner auxiliary waveguides and an adjacent one of the outer auxiliary waveguides tapers in the light propagation direction, wherein within at least a portion of the second section, the spacing distance between the one of the inner auxiliary waveguides and the adjacent one of the outer auxiliary waveguides is zero.

[015] In some embodiments, the upper layers include at most two layers of auxiliary waveguides.

[016] In some embodiments, the auxiliary waveguides of each upper layer include at most four auxiliary waveguides.

[017] In some embodiments, the layered arrangement includes an initial section which adjoins the first section and is distal from the second section, wherein within the initial section, the width of each auxiliary waveguide is non-tapered.

[018] In some embodiments, within the second section, the outer auxiliary waveguides are formed to converge towards an axial plane of the SOI waveguide.

[019] In some embodiments, within the first section, the width of each auxiliary waveguide widens linearly in the light propagation direction.

[020] In some embodiments, a device footprint of the spot-size converter is at most 345 μm .

[021] In some embodiments, each auxiliary waveguide includes silicon nitride, silicon oxynitride or aluminium nitride, and wherein the cladding material includes silicon oxide or silicon dioxide.

BRIEF DESCRIPTION OF THE DRAWINGS

[022] The drawings are for illustration only and do not limit the invention wherein:

[023] Figure 1 is a see-through view taken from a top of an embodiment of a spot-size converter;

[024] Figures 2A to 2C are cross-sectional views of the spot-size converter respectively taken along lines A-A', B-B' and C-C' indicated in Figure 1;

[025] Figure 3 illustrates a simulated optical mode profile at the front facet of a spot-size converter at 1550 nm for transverse electric (TE) mode excitation;

[026] Figure 4A illustrates a measured optical loss spectrum for a spot-size converter at telecommunication C-band and L-band obtained from 5 fabricated samples; and Figure 4B illustrates the corresponding 1-dB misalignment tolerance window along the lateral axis, i.e., orthogonal to the substrate surface normal;

[027] Figures 5A to 5F show isometric views of various multilayer edge coupler schemes wherein Figures 5A to 5E show conventional multilayer edge couplers while Figure 5F shows a spot-size converter according to an embodiment of the invention.

DETAILED DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

[028] In the following description, numerous specific details are set forth in order to provide a thorough understanding of various illustrative and non-limiting embodiments. It will be understood, however, to one skilled in the art, that embodiments of the invention may be practiced without some or all these specific details. It is understood that the terminology used herein is for the purpose of describing particular embodiments only, and is not intended to limit the scope of the invention. In the drawings, like reference labels or numerals, refer to same or similar functionalities or features throughout the several views.

[029] Embodiments described in the context of one of the devices or methods are analogously valid for the other devices or methods. Similarly, embodiments described in the context of a device are analogously valid for a method, and vice versa.

[030] Features that are described in the context of an embodiment may correspondingly be applicable to the same or similar features in the other embodiments. Features that are described in the context of an embodiment may correspondingly be applicable to the other embodiments, even if not explicitly described in these other embodiments. Furthermore, additions and/or combinations and/or alternatives as described for a feature in the context of an embodiment may correspondingly be applicable to the same or similar feature in the other embodiments.

[031] It should be understood that the articles "a", "an" and "the" as used with regard to a feature or element include a reference to one or more of the features or elements. The term "and/or" includes any and all combinations of one or more of the associated feature or element. The terms "comprising", "including", "having", and any of their related terms, as used in description and claims, are intended to be open-ended and mean that there may be additional features or elements other than the listed ones. Identifiers such as "first", "second", "third", and so on, are used merely as labels, and are not intended to impose numerical requirements on their objects, nor construed in a manner imposing any relative position or time sequence between limitations. The term "to" may include a reference to "configured to", "adapted to", and "constructed and arranged to" which may be used interchangeably. Furthermore, terms such as "top", "bottom", "upper", "lower", "under", "over", "on" and their related terms used herein are merely for ease of description and may refer to the orientation of the features or elements as shown in the figures. It should be understood that any orientation of the features described herein is within the scope of the invention.

[032] The term "coupled" may be used to include a reference to operational sense and may also include, but not necessarily limited to, a physical, optical, and/or electrical connection or coupling which may be direct or indirect. Thus, for example, two devices may be coupled directly, or indirectly via one or more intermediary devices. Based on the present disclosure, a person of ordinary skill in the art will appreciate a variety of ways in which coupling exists in accordance with the aforementioned definition.

[033] The term "length" and its related terms refer to a dimension of an element in the light propagation direction and along a longitudinal axis which is shown as x-axis in the figures. The term "width" and its related terms refer to a dimension of an element perpendicular to the light propagation. The term "height" and its related terms refer to a dimension of an element perpendicular to both the length and width. In some instances, the term "height" may be alternatively referred to by the term "thickness". The term "vertical" refers to a direction which is along the "height" (or "thickness") direction. Likewise, the term "horizontal" refers to a direction lying in a plane which is perpendicular to the vertical direction, and which encompasses the "width" and "length" directions.

[034] The term “layer” may include a combination two or more layers or sub-layers. The term “cover” may refer to cover partially or fully.

[035] In view of the above-described and other issues with existing solutions, there is a need to reduce coupling loss between silicon-on-insulator (SOI) photonics chips and standard single-mode fibers without deteriorating mechanical robustness of edge couplers.

[036] Furthermore, existing solution utilises multiple layers of auxiliary waveguides to facilitate spot-size conversion of light from a single-mode fiber (SMF) to a waveguide with submicron feature sizes. However, existing solution still lacks a device that is able to facilitate efficient optical power coupling from a standard SMF, e.g., SMF28e, with mode field diameter (MFD) of 10.4 μm at 1550 nm to a single-mode SOI waveguide in a short device footprint with low cost, e.g., less mask set.

[037] Embodiments of the invention provide a spot-size converter or device which comprises a layered arrangement having upper layers and at least one lower layer. The upper layers include a plurality of cladded tapered auxiliary waveguides while the lower layer includes a cladded SOI waveguide. In each upper layer, the auxiliary waveguides include inner auxiliary waveguides and outer auxiliary waveguides. The layered arrangement includes at least two sections arranged contiguously along a light propagation direction. In the first section, the auxiliary waveguides are configured to convert the spot size from a larger MFD supported by a standard SMF to a mode with smaller spot size supported by the underneath SOI waveguide. This is achieved by increasing or widening the width of each auxiliary waveguide in the light propagation direction. The SOI waveguide is introduced within this first section after some propagation length to facilitate the adiabatic transition of the mode to the SOI waveguide. In the second section, the outer auxiliary waveguides converge towards each other. This convergence arrangement helps maintain adiabatic coupling of the mode from the auxiliary waveguides to the underneath SOI waveguide. Thus, adiabatic coupling from the auxiliary waveguides to the SOI waveguide is more efficient, thus enabling smaller device footprint.

[038] Figure 1 is a see-through view taken from a top of an embodiment of a spot-size converter 100. Figures 2A to 2C are cross-sectional views of the spot-size converter 100 respectively taken along lines A-A', B-B' and C-C' indicated in Figure 1.

[039] The layered arrangement, collectively, has a longitudinal direction (x-direction) which is defined in a light propagation direction (see arrow 10 in Figure 1), a lateral direction (y-direction) which is transverse to the longitudinal direction or light propagation direction 10, and a height direction (z-direction) which is transverse to the longitudinal direction and the lateral direction. The layered arrangement, collectively, includes at least a first section and an adjoining second section which are contiguously arranged in the longitudinal direction. The light propagation direction 10 is taken to initially traverse the first section followed by the second section. The layered arrangement, collectively, may further include an initial section which precedes the first section. In other words, the first section is interposed between the initial section and the second section. Hence, the light propagation direction 10 is taken to initially traverse the initial section followed by the first section and the second section in this sequence.

[040] The layered arrangement includes a plurality of identical upper layers overlaying at least one lower layer. Each upper layer includes a plurality of lateral array of auxiliary waveguides which include a plurality of inner auxiliary waveguides and a plurality of outer auxiliary waveguides. In this embodiment, four auxiliary waveguides are provided which include two inner auxiliary waveguides 106, 116, 108, 118 interposed between two outer auxiliary waveguides 102, 112, 104, 114. The inner auxiliary waveguides 106, 116, 108, 118 may be non-identical to the outer auxiliary waveguides 102, 112, 104, 114. The inner auxiliary waveguides 106, 116, 108, 118 may be identical to each other. The outer auxiliary waveguides 102, 112, 104, 114 may or may not be identical to each other. The layouts of auxiliary waveguides on each of the upper layers are identical. Thus, auxiliary waveguides of adjacent upper layers overlay or superimpose on each other.

[041] Each auxiliary waveguide traverses the initial section (where applicable), the first section, and the second section. Accordingly, each auxiliary waveguide has a length defined in the longitudinal direction, a width defined in the lateral direction, and

a thickness is defined in the height direction. The length of each auxiliary waveguide includes its length traversing the initial section (where applicable) which may be denoted by d_1 , its length traversing the first section which may be denoted by d_3 , and its length traversing the second section which may be denoted by d_5 . The width of each auxiliary waveguide varies as described in the following paragraphs. The thickness of each auxiliary waveguide may remain constant or non-tapered. Each auxiliary waveguide may include silicon nitride (SiN), silicon oxynitride (SiON), aluminium nitride (AlN), a material having similar refractive index as SiN, SiON or AlN, or other suitable material.

[042] Within the initial section, a width of each auxiliary waveguide is constant or non-tapered. Referring to Figure 1, in an initial section having a length of d_1 , each auxiliary waveguide has a constant width of w_1 as it extends along length d_1 in the light propagation direction 10 while a spacing between adjacent auxiliary waveguides has a constant spacing distance of s_1 . The initial section includes two opposed edges in the light propagation direction 10 wherein one of the edges which is non-adjointing to or more distal from the first section is an interfacing edge configured to interface with a SMF. Hence, each auxiliary waveguide is introduced at the interfacing edge.

[043] Within the first section, a width of each auxiliary waveguide 102, 104, 106, 108 is tapered. Referring to Figure 1, in a first section having a length d_3 , each auxiliary waveguide 102, 104, 106, 108 has an increasing width, from w_1 to w_2 , along length d_3 in the light propagation direction 10, i.e., $w_1 < w_2$. In other words, within the first section, a width of each auxiliary waveguide 102, 104, 106, 108 widens or inversely tapers in the light propagation direction 10. Adjacent auxiliary waveguides 102, 104, 106, 108 collectively have a decreasing or tapered spacing distance, from s_1 to s_2 , along length d_3 in the light propagation direction 10, i.e., $s_1 > s_2$. In other words, within the first section, a spacing distance between adjacent auxiliary waveguides 102, 104, 106, 108 tapers or narrows in the light propagation direction 10.

[044] Within the second section, a width of each auxiliary waveguide 112, 114, 116, 118 is constant or non-tapered. Referring to Figure 1, in a second section having a length d_5 , each auxiliary waveguide 112, 114, 116, 118 has a constant width w_2 along length d_5 in the light propagation direction 10. The inner auxiliary waveguides 116, 118

are arranged parallel to each other. As such, a spacing distance between the inner auxiliary waveguides 116, 118 is constant or non-tapered at s_2 . The outer auxiliary waveguides 112, 114 are arranged non-parallel to each other, e.g., converge towards each other such as towards an axial plane of a SOI waveguide 110. This axial plane is shown in Figure 1 by a white dashed line traversing the SOI waveguide 110. As such, a spacing distance between each outer auxiliary waveguide 112, 114 and its adjacent inner auxiliary waveguide 116, 118 tapers from s_2 to s_3 along length d_5 in the light propagation direction 10, i.e. $s_2 > s_3$.

[045] It is to be appreciated that portions of an auxiliary waveguide which traverse the first section and the second section are integrally formed or joined to provide a unitary structure, i.e., portions 102 and 112 provide a single auxiliary waveguide; the same applies to portions 104 and 114, portions 106 and 116, portions 108 and 118.

[046] The lower layer includes a SOI structure which includes a silicon substrate 122, a silicon oxide 120 (buried oxide) arranged on the silicon substrate 122, and a silicon nanotaper 110, which provides the SOI or routing waveguide, arranged on the insulator. The SOI waveguide has a length defined in the longitudinal direction, a width defined in the lateral direction, and a thickness in defined in the height direction. Referring to Figure 1, the SOI waveguide 110 has a length d_4 , a tapered width, and a non-tapered or constant thickness. The SOI waveguide 110 does not traverse the initial section; the SOI waveguide 110 partially traverses with the first section and fully traverses the second section. The SOI waveguide 110 is introduced to the first section after a propagation length d_2 from the start point of the first section, e.g., at a position within the first section where efficient adiabatic mode transition between the mode supported by the auxiliary waveguides 102, 112, 104, 114, 106, 116, 108, 118 and the mode supported collectively with the underneath SOI waveguide 110 can be facilitated. At the introduction position of length d_4 , the SOI waveguide 110 has a width w_3 which increases or widens to w_4 at a termination position of length d_4 , i.e., $w_3 < w_4$. In other words, a width of the SOI waveguide 110 widens or inversely tapers in the light propagation direction 10.

[047] The SOI waveguide 110 includes an axial plane which extends in the height direction along a centre axis of the SOI waveguide 110. This axial plane is shown in Figure 1 by a dashed line traversing the SOI waveguide 110.

[048] A cladding 120 is arranged to cover or surround the auxiliary waveguides 102, 112, 104, 114, 106, 116, 108, 118 and the SOI waveguide 110, at least in the longitudinal direction. In particular, the cladding 120 is interposed between adjacent layers of the layered arrangement and between the auxiliary waveguides 102, 112, 104, 114, 106, 116, 108, 118. In other words, the auxiliary waveguides 102, 112, 104, 114, 106, 116, 108, 118 and the SOI waveguide 110 are embedded in the cladding 120. The cladding 120 has a length defined in the longitudinal direction, a width defined in the lateral direction, and a thickness defined in the height direction. The cladding 120 may include silicon oxide, silicon dioxide, or other suitable material.

[049] Referring to Figures 2A to 2C, the cross-sectional views show two upper layers of auxiliary waveguides 102, 112, 104, 114, 106, 116, 108, 118 arranged on a lower layer of SOI waveguide 110. In the upper layers, the auxiliary waveguides 102, 112, 104, 114, 106, 116, 108, 118 have a thickness of t_1 or t_2 which is constant or non-tapered throughout the first section and the second section where t_1 and t_2 may be equal, i.e., $t_1 = t_2$. Thickness of the SOI waveguide 110 t_3 may be unequal to t_1 and t_2 .

[050] A spacing distance in the height direction between the silicon substrate 122 and the SOI waveguide 110 is i_4 . A spacing distance in the height direction between the SOI waveguide 110 and auxiliary waveguides 102, 112, 104, 114, 106, 116, 108, 118 in the upper layer most adjacent to the SOI waveguide 110 is i_1 . A spacing distance in the height direction between auxiliary waveguides 102, 112, 104, 114, 106, 116, 108, 118 of adjacent upper layers is i_2 . A spacing distance in the height direction between auxiliary waveguides 102, 112, 104, 114, 106, 116, 108, 118 in the most distal layer from the SOI waveguide 110 and a top edge of the layered arrangement is i_3 .

[051] Within the aforementioned spacing distances i_1 to i_4 taken in the height direction and spacing distances s_1 to s_3 taken in the lateral direction, a cladding 120 is provided which covers or surrounds the auxiliary waveguides 102, 112, 104, 114, 106, 116, 108, 118 and SOI waveguide 110. Accordingly, the spacing distances i_1 to i_4 may

alternatively be referred to cladding thicknesses i_1 to i_4 respectively; the spacing distances s_1 to s_3 may alternatively refer to cladding widths s_1 to s_3 respectively.

[052] It is to be appreciated that modifications may be made to the illustrated embodiment.

[053] In the illustrated embodiment, within the first section, the width of each auxiliary waveguide widens (or inverse tapers) linearly in the light propagation direction. However, in an alternative embodiment, this width of each auxiliary waveguide may widen (or inverse taper) non-linearly. Non-linear inverse taper may be an inverse parabolic taper. In another alternative embodiment, this width of each auxiliary waveguide may widen linearly along a portion of its length and widen non-linearly along another portion of its length.

[054] In the illustrated embodiment, the width of the SOI waveguide widens (or inverse tapers) linearly in the light propagation direction. However, in an alternative embodiment, this width of the SOI waveguide may widen (or inverse taper) non-linearly. In another alternative embodiment, this width of the SOI waveguide may widen linearly along a portion of its length and widen non-linearly along another portion of its length.

[055] In the illustrated embodiment, within the first section of each upper layer, a spacing distance in the lateral direction between the adjacent auxiliary waveguides taper linearly in the light propagation direction. However, in an alternative embodiment, this spacing distance between adjacent auxiliary waveguides may taper non-linearly. Non-linear taper may be a parabolic taper. In another alternative embodiment, this spacing distance may widen linearly along a portion of the length and widen non-linearly along another portion of the length.

[056] In the illustrated embodiment, within the second section of each upper layer, a spacing distance in the lateral direction between the inner auxiliary waveguide is constant or non-tapered, e.g., a spacing distance between auxiliary waveguides 116 and 118 is s_2 throughout the second section. However, in an alternative embodiment,

this spacing distance between auxiliary waveguides 116 and 118 may taper or narrow in the light propagation distance.

[057] In the illustrated embodiment, within both the first section and the second section of each upper layer, a spacing distance in the lateral direction between one of the inner auxiliary waveguides and an adjacent one of the outer auxiliary waveguides tapers in the light propagation direction. With particular reference to Figure 1, within the first section, a spacing between an inner and an outer auxiliary waveguide 106, 102 narrows from s_1 to s_2 in the light propagation direction 10; within the second section, a spacing between the same inner and outer auxiliary waveguides 116, 112 further narrows from s_2 to s_3 in the same direction, where $s_1 > s_2 > s_3$. This tapered or narrowed spacing within the second section is configured to confine the mode towards the axial plane of the SOI waveguide 110. However, in an alternative embodiment, while a spacing between an inner and an outer auxiliary waveguide 106, 102 narrows from s_1 to s_2 in the light propagation direction 10, a spacing distance between the same inner and outer auxiliary waveguides 116, 112, may be constant or non-tapered within the second section. This non-tapered spacing within the second section would not be configured to confine the mode towards the axial plane of the SOI waveguide. However, in yet another alternative embodiment, this spacing between the inner and outer auxiliary waveguides 116, 112, may taper to zero within at least a portion of the second section or be maintained at zero throughout the second section if mode coupling to the underneath SOI waveguide is completed. In the absence of this spacing, the inner and outer auxiliary waveguides 116, 112 may be arranged adjoining or in physical contact with each other. The description and modifications in this paragraph also apply to other auxiliary waveguides 106, 102 in the first section and other auxiliary waveguides 114, 118 in the second section.

[058] In the illustrated embodiment, the upper layers include two layers of auxiliary waveguides. In a non-limiting example, the upper layers include at most two layers of auxiliary waveguides. However, in some alternative embodiments, the upper layers may include at least two layers of auxiliary waveguides, e.g., two, three, four, or more layers.

[059] In the illustrated embodiment, the auxiliary waveguides of each upper layer include four auxiliary waveguides. In a non-limiting example, the auxiliary waveguides of each upper layer include at most four auxiliary waveguides. However, in some alternative embodiments, the auxiliary waveguides of each upper layer may include at least two auxiliary waveguides, e.g., two, four, six, or a higher even number of auxiliary waveguides.

[060] In the illustrated embodiment, the layered arrangement includes an initial section which adjoins the first section and is distal from the second section, wherein within the initial section, the width of each auxiliary waveguide is non-tapered. In an alternative embodiment, the layered arrangement includes at most the first section and the second section, i.e., the layered arrangement is devoid of additional sections.

[061] In a non-limiting example of the illustrated embodiment, a device footprint of the spot-size converter is at most 345 μm . Device footprint references to a length between left-most edge and right-most edge of the device, e.g., summation of d_1 , d_2 and d_4 as shown in Figure 1. In this example, where d_1 is 5 μm , d_3 is 200 μm , d_5 is 100 μm , an extension of the SOI waveguide 110 which is beyond the second section is 40 μm , the total spot-size converter length is 345 μm .

[062] In the illustrated embodiment, at least within the first section, the auxiliary waveguides have a symmetric taper profile, e.g., symmetric about the longitudinal direction. In an alternative example, the auxiliary waveguides may have a non-symmetric taper profile.

[063] It is to be appreciated that two or more of the above-described alternative embodiments may be suitably combined.

[064] Figure 3 shows an optical mode profile simulated for an embodiment of the invention disclosure at the edge of the spot-size converter device at 1550 nm for TE mode excitation.

[065] Figure 4A shows a measured coupling loss spectrum and Figure 4B shows a measured lateral misalignment tolerance along the lateral axis, i.e., orthogonal to the

substrate surface normal and light propagation direction 10. The device exhibits a total coupling loss of 2.01 ± 0.08 dB/facet including the mode coupling loss to the underneath SOI waveguide with a flat band response across the C-band and L-band and the excess coupling loss is kept within 1 dB within 5.0 μm alignment window.

[066] Figures 5A to 5F shows isometric views of various multilayer edge coupler schemes. Particularly, Figures 5A to 5E show conventional multilayer edge couplers while Figure 5F shows a spot-size converter according to an embodiment.

[067] Figure 5A shows a structure 510 which comprises three juxtaposed layers of SiN waveguides. In the top layer 511, the waveguide widens in the light propagation direction 10. In the middle layer 512 and the bottom layer 513, the waveguides taper in the light propagation direction 10. In operation, light couples from a SMF with an MFD of 10.4 μm to the waveguide of the top layer 511.

[068] Figure 5B shows a structure 520 that comprises three juxtaposed layers 521, 522, 523 of SiN waveguides and an underlying SOI nanotaper 524. Each layer includes three waveguides. The waveguides in the juxtaposed three layers are non-tapered, i.e., rod waveguides, and are configured to create a super-mode at the coupling interface with a SMF. In operation, light couples from a SMF with an MFD of 6.0 μm to the underneath SOI nanotaper which widens in the light propagation direction 10.

[069] Figure 5C shows a structure 530 that comprises three juxtaposed layers 531, 532, 533 of SiN waveguides and an underlying SOI nanotaper 524. Each layer includes four waveguides. The waveguides in the juxtaposed three layers are non-tapered, i.e., rod waveguides, and are configured to create a super-mode at the coupling interface with a SMF. In operation, light couples from a SMF with an MFD of 10.4 μm to the underneath SOI nanotaper which widens in the light propagation direction 10.

[070] Figure 5D shows a structure 540 that comprises two juxtaposed layers 541, 542 of SiN waveguides and an underlying SOI nanotaper 543. In the top layer 541 having three waveguides, the waveguides are non-tapered, i.e., rod waveguides. In

the bottom layer 542 having one waveguide, the waveguide widens in the light propagation direction 10. The underneath SOI nanotaper 544 also widens in the light propagation direction 10. In operation, light couples from a SMF with an MFD of 10.4 μm to the bottom SiN tapered waveguide 544.

[071] Figure 5E shows a structure 550 that comprises alternating layers of SiN waveguides 551 and silicon oxide 552 in mesa-like shape formed via etching process. The introduction of thin SiN layers increases the effective index of the structure 550 at the coupling interface. The underneath SOI nanotaper 553 widens in the light propagation direction 10. In operation, light couples from a SMF with an MFD of 10.4 μm to underneath SOI waveguide 553.

[072] Figure 5F shows an embodiment wherein the structure 560 comprises two juxtaposed layers 561, 562 of SiN and an underlying SOI nanotaper 563. Each layer contains four SiN waveguides and is arranged in two sections. The first section comprises four SiN nanotapers that widens in the light propagation direction. The first section is followed by a second section of four SiN waveguides that are non-tapered, but the outer waveguides converge towards each other, e.g., the axial centre of the underneath SOI waveguide to improve the adiabatic mode conversion. In operation, light couples from a SMF with a MFD of 10.4 μm to the underneath SOI nanotaper.

[073] Embodiments of the invention provide various advantages such as but not limited to the following.

[074] A spot-size converter structure according to embodiments of the invention facilitates efficient optical coupling from a standard SMF to a underneath SOI single-mode waveguide. The non-suspended nature of the structure benefits fiber optic packaging of silicon photonics chips as the structure is more robust, i.e., less susceptible to mechanical failures, than conventional suspended edge couplers which are less robust and prone to waveguide collapse and tip damage due to undercut etching to produce a cavity at its silicon substrate. Furthermore, the spot-size converter according to embodiments of the invention is oil-free, i.e., devoid of any index matching oil.

[075] Unlike some conventional edge couplers that use three or more SiN or SiON waveguide layers, at least some embodiments of the invention utilize a double-layer design that simplifies fabrication process yet achieves on-par coupling performance. Besides, only one mask set is needed to define the patterns of the auxiliary waveguides in each layer, keeping the reticle cost low. Moreover, the use of double layers prevents the mechanical stress across the wafer that would have been induced by a thicker film otherwise.

[076] Unlike some conventional edge couplers wherein the auxiliary waveguides are arranged in cross-like formation, at least some embodiments of the invention use the same waveguide patterns in each layer with one mask set.

[077] Unlike some conventional edge couplers wherein light is coupled to one of the waveguides forming the auxiliary waveguide set, e.g., SiN, at least some embodiments of the invention couple light to SOI waveguide with which electro-optic modulators and photodetectors can be made of via ion implantation.

[078] Unlike some conventional edge couplers wherein the auxiliary waveguides are made of slab waveguides which require additional etching steps to form a mesa structure for mode matching, at least some embodiments of the invention use embedded waveguides and do not necessitate the etching step in the formation of auxiliary waveguides.

[079] Unlike some conventional edge couplers wherein the auxiliary waveguides are non-tapered but like rods, at least some embodiments of the invention adopt a double-staged or double-sectioned auxiliary waveguide arrangement wherein the first section transforms a large mode size from the fiber coupling interface to a smaller mode size supported by the underneath SOI routing waveguide whereas the adiabatic coupling of optical mode from auxiliary waveguides is maintained during the second stage which structurally converges to the axial center of the spot-size converter. Thus, compared to rod-like designs, embodiments of the invention facilitate more efficient adiabatic coupling from the auxiliary waveguides to the SOI waveguide which enables smaller device footprint. The shorter device length is achieved by the use of double-staged auxiliary waveguide formation wherein the first section transforms the mode

size to be compatible with the mode supported by the underneath SOI waveguide while the second section of the auxiliary waveguides facilitates adiabatic transition while structurally converging to the axial center of the device.

[080] Thus, for the illustrated embodiment comprising double layers of auxiliary SiN waveguides in quadruple-tapers formation per layer embedded in silicon oxide cladding to couple light from a standard SMF with MFD of 10.4 μm at 1550 nm to a SOI waveguide, this embodiment achieves 2 dB/facet coupling loss at 1550 nm for TE polarization in a shorter device length of 345 μm , as compared to prior literature. Furthermore, 1-dB lateral misalignment tolerance is superior to conventional suspended edge couplers.

[081] It is to be understood that the embodiments and features described above should be considered exemplary and not restrictive. Many other embodiments will be apparent to those skilled in the art from consideration of the specification and practice of the invention. Furthermore, certain terminology has been used for the purposes of descriptive clarity, and not to limit the disclosed embodiments of the invention.

Claims

1. A spot-size converter comprising:

a layered arrangement having a first section and an adjoining second section which are arranged in a light propagation direction which is to traverse the first section followed by the second section, the layered arrangement having a plurality of upper layers and a lower layer, wherein each upper layer includes a plurality of auxiliary waveguides which include a plurality of inner auxiliary waveguides and a plurality of outer auxiliary waveguides, wherein the lower layer includes a silicon-on-insulator (SOI) waveguide which partially traverses the first section and fully traverses the second section, wherein a width of the SOI waveguide widens in the light propagation direction; and

a cladding covering the auxiliary waveguides and the SOI waveguide,

wherein within the first section, a width of each auxiliary waveguide widens in the light propagation direction, wherein within the second section, the width of each auxiliary waveguide is non-tapered and the outer auxiliary waveguides are arranged to converge towards each other.

2. The spot-size converter of claim 1, wherein within the first section, a spacing between the inner auxiliary waveguides tapers in the light propagation direction, wherein within the second section, the spacing distance between the inner auxiliary waveguides is non-tapered.
3. The spot-size converter of any one of claim 1 to claim 2, wherein within the first section and the second section, a spacing distance between one of the inner auxiliary waveguides and an adjacent one of the outer auxiliary waveguides tapers in the light propagation direction.
4. The spot-size converter of any one of claim 1 to claim 2, wherein within the first section, a spacing distance between one of the inner auxiliary waveguides and an adjacent one of the outer auxiliary waveguides tapers in the light propagation direction, wherein

within the second section, the spacing distance between the one of the inner auxiliary waveguides and the adjacent one of the outer auxiliary waveguides is non-tapered.

5. The spot-size converter of any one of claim 1 to claim 2, wherein within the first section, a spacing distance between one of the inner auxiliary waveguides and an adjacent one of the outer auxiliary waveguides tapers in the light propagation direction, wherein within at least a portion of the second section, the spacing distance between the one of the inner auxiliary waveguides and the adjacent one of the outer auxiliary waveguides is zero.
6. The spot-size converter of any one of claim 1 to claim 5, wherein the upper layers include at most two layers of auxiliary waveguides.
7. The spot-size converter of claim 6, wherein the auxiliary waveguides of each upper layer include at most four auxiliary waveguides.
8. The spot-size converter of any one of claim 1 to claim 7, the layered arrangement having an initial section which adjoins the first section and is distal from the second section, wherein within the initial section, the width of each auxiliary waveguide is non-tapered.
9. The spot-size converter of any one of claim 1 to claim 8, wherein within the second section, the outer auxiliary waveguides are formed to converge towards an axial plane of the SOI waveguide.
10. The spot-size converter of any one of claim 1 to claim 9, wherein within the first section, the width of each auxiliary waveguide widens linearly in the light propagation direction.
11. The spot-size converter of any one of claim 1 to claim 10, wherein a device footprint of the spot-size converter is at most 345 μm .
12. The spot-size converter of any one of claim 1 to claim 11, wherein each auxiliary waveguide includes silicon nitride, silicon oxynitride or aluminium nitride, and wherein the cladding material includes silicon oxide or silicon dioxide.