

EDGE COUPLER HAVING SUSPENDED WAVEGUIDE WITH IMPROVED MECHANICAL RIGIDITY

TECHNICAL FIELD

[001] The present disclosure relates to structures for silicon photonics edge coupler, optical packaging, optical fibre coupler, suspended edge coupler, and methods for fabricating such structures.

BACKGROUND

[002] Low loss coupling of light into and out of photonic chips is desired to reduce costs of optical communication links.

[003] Existing approaches attempt to achieve efficient coupling between a silicon waveguide and a single-mode fibre (SMF) include surface gratings and spot-size converters (SSC) such as inverse tapers, suspended edge couplers, multi-layer edge couplers. However, existing approaches 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 their operation is based on mode overlap. However, the modal expansion is limited by substrate leakage due to the proximity of the silicon (Si) substrate to buried oxide (BOX) layer. Even though a low coupling loss is achievable for fibres with small mode-field diameters (MFD), the coupling loss substantially increases for standard single-mode fibres. Besides, such edge couplers have very small misalignment tolerances due to their small MFD.

[006] Edge couplers comprising multi-layer spot-size converter help mitigate substrate leakage problem and provide relaxed misalignment tolerances. These devices comprise a few layers of lower-index waveguides (e.g., silicon nitride) that have cladding material between layers (e.g., silicon oxide, silicon oxynitride) and

positioned atop standard waveguide layer (e.g., silicon-on-insulator). However, the layered stack to form multi-layer edge coupler increases the integration process complexity and multi-layer deposition of lower-index waveguide and the cladding in between increases the overall film stress across the wafer.

[007] In silicon-on-insulator based photonics platforms, an alternative edge coupler approach provides for the silicon oxide top cladding material together with the bottom cladding material (alternatively referred to as BOX layer) to define the coupling waveguide. This is achieved by isolating the silicon oxide top cladding and the BOX layer from the silicon substrate via a series of etching steps and creating a suspended oxide waveguide comprising top oxide cladding and BOX layer above the silicon substrate. The phrase 'silicon oxide' and the term 'oxide' are equivalent and may be used interchangeably hereinafter.

[008] The suspended oxide waveguide is isolated from the rest of the top cladding and BOX layer as well as the bulk substrate so that substrate leakage is prevented. Besides, the width of the suspended oxide waveguide can be tailored to match the mode size of the input beam.

[009] Moreover, since the coupling waveguide is made of silicon oxide, refractive indices of silica optical fibre and coupling waveguide will be similar, thus minimizing the Fresnel reflection. Should the coupling interface be immersed within a suitable index-matching oil, suspended edge couplers can achieve coupling loss down to 1.0 dB/facet.

[010] In silicon-on-insulator based photonics platforms, isolation of a silicon oxide coupling waveguide is achieved by first etching the cladding material down to the silicon substrate. This is followed by isotropic silicon etch, wherein the structure is being etched towards the silicon substrate by a few tens of microns. This allows for defining the coupling waveguide out of the silicon oxide which is cladded by air.

[011] The hundreds-of-microns-long suspended waveguide is connected to bulk top oxide cladding through a row of oxide support rods on both sides to prevent collapse.

[012] The support rods with small feature sizes are desirable in order not to perturb the optical mode propagating through the suspended oxide waveguide. However, this imposes a design trade-off as support rods with wider feature size improve mechanical support against shakes, vibrations, and shear effect.

[013] This is especially important in densely integrated multi-input/output coupling schemes, e.g., a photonic integrated circuit where a closely spaced row of suspended edge couplers is used as an optical phased array emitter/receiver block. In such use cases, the suspended edge couplers with oxide support rods of small feature size become more susceptible to waveguide collapse and/or breakage as support rod width can be further diminished due to the aggregate effect of isotropic silicon etch of adjacent waveguides.

[014] FIGs. 1A, 1B and 1C illustrate a conventional suspended edge coupler 100 with oxide support rods in rectangular footprint.

[015] The conventional suspended edge coupler 100 includes a suspended oxide waveguide 102, rows of isolation trenches 104 on both sides of the suspended oxide waveguide 102, a row of oxide support rods having rectangular footprint 106 and arranged on both sides of the suspended oxide waveguide 102 to provide mechanical support, a nano-taper 108 to facilitate adiabatic coupling of light from the suspended oxide waveguide 102 into a silicon waveguide 110.

[016] While many existing approaches focus on optimizing coupling performance, very few approaches are concerned about mechanical reliability or rigidity of the suspended edge couplers.

SUMMARY

[017] According to a first aspect, an edge coupler comprises:

a suspended waveguide having a longitudinal direction and a lateral direction,
the waveguide arranged between two longitudinal rows of periodic isolation trenches
an outer cladding;

a plurality of lateral support rods arranged between the isolation trenches and interconnecting the waveguide and the outer cladding;

a silicon substrate having a cavity in fluid communication with the isolation trenches, wherein the waveguide and the support rods are suspended over the cavity, wherein the outer cladding is supported by the substrate; and

an inverse taper of a second waveguide which is embedded in the suspended waveguide,

wherein each support rod includes a footprint having a first edge width interfacing the waveguide, and a second edge width interfacing the cladding, wherein the second edge width is larger than the first edge width.

[018] According to a second aspect, a method for fabricating an edge coupler, the method comprising:

forming a top cladding on a silicon-on-insulator (SOI) structure which includes a silicon layer which is formed on a buried oxide (BOX) layer which is formed on a silicon substrate;

without etching the silicon substrate, pattern etching the top cladding and the SOI structure with two longitudinal rows of periodic isolation trenches to define an inner cladding between the two longitudinal rows of periodic isolation trenches, an outer cladding separated from the inner cladding by one of the two longitudinal rows of periodic isolation trenches, and lateral support rods interconnecting the inner cladding and the outer cladding;

isotropic etching the silicon substrate to cause suspension of the inner cladding to provide a suspended waveguide;

wherein each support rod includes a footprint having a first edge width interfacing the suspended waveguide, and a second edge width interfacing the outer cladding, wherein the second edge width is larger than the first edge width, and wherein the first waveguide includes an inverse taper of a second waveguide.

BRIEF DESCRIPTION OF THE DRAWINGS

[019] FIGs. 1A, 1B, and 1C illustrate a top view, a partial close-up view, and a front cross-sectional view of a conventional suspended edge coupler with rectangular support rods;

[020] FIGs. 2A, 2B, and 2C respectively illustrate a top view, a partial close-up view and a front cross-section view of a suspended edge coupler with support rods in isosceles trapezoid footprint in accordance with an embodiment of the present disclosure;

[021] FIG. 2D illustrates a top view of the support rod of FIGs. 2A, 2B, and 2C;

[022] FIGs. 3A, 3B, 3C, and 3D illustrate support rods of different shapes; and

[023] FIG. 4 illustrates the measured optical loss spectrums of a conventional suspended edge coupler with rectangular support rod design where $w_1 = w_2 = 2 \mu\text{m}$, and one of the embodiments where the isosceles trapezoid oxide support rod design has design parameters of $w_1 = 2 \mu\text{m}$ and $w_2 = 10 \mu\text{m}$.

DETAILED DESCRIPTION

[024] 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 of 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.

[025] 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.

[026] 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.

[027] 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.

[028] In view of existing approaches, there remains a need to improve mechanical rigidity and robustness of suspended edge couplers without deteriorating their coupling performance. Accordingly, suspended edge couplers disclosed herein provide a solution to improve the mechanical rigidity of the suspended edge couplers through oxide support rods in which a support rod width on the edge interfacing the suspended oxide waveguide is narrower than a support rod width on the opposite edge interfacing the bulk cladding layer.

[029] Embodiments of the present disclosure provide optical edge couplers suitable for use in photonic waveguides constructed on silicon-on-insulator based photonics platforms.

[030] FIGs. 2A, 2B, and 2C illustrate various views of an embodiment of a suspended edge coupler 200 with support rods having isosceles trapezoid footprints.

[031] The edge coupler 200 comprises a suspended or first waveguide 202, a top oxide cladding 212, a bottom oxide cladding 214 (alternatively referred to as buried oxide (BOX) layer), longitudinal rows of periodically-arranged isolation trenches 204, lateral rows of periodically-arranged support rods 206, an inverse taper 208, and a substrate 216.

[032] The suspended waveguide 202 includes a longitudinal direction (z-direction shown in FIG. 2A) which corresponds to an axis of optical signal or light propagation, and a lateral direction (x-direction shown in FIG. 2A) which is transverse to the longitudinal direction. The waveguide 202 includes opposed sidewalls wherein each side wall extends along or substantially along the longitudinal direction. The waveguide 202 includes opposed ends, e.g., a first end and a second end, wherein light is to propagate from the first end towards the second end. The waveguide 202 is arranged or interposed between two longitudinal rows of periodic isolation trenches 204, e.g., each pair of neighbouring isolation trenches 204 within a same longitudinal row of trenches are separated by a support rod 206. The isolation trenches 204 extend along or substantially along the longitudinal direction. The waveguide 202 includes a lateral dimension D which tapers or gradually narrows along the longitudinal direction, e.g., the lateral dimension of the waveguide 202 is larger at its first end than at its second end. In some examples, a minimum lateral dimension of the waveguide 202 may be $\geq 2\ \mu\text{m}$ as smaller values may result in very-thin or fully-etched region between laterally adjacent trenches. Such resulting very thin structure may subsequently collapse under a thick oxide layer which may be about $6\ \mu\text{m}$. It is to be appreciated that the minimum lateral dimension of the waveguide 202 may vary depending on fabrication specification.

[033] The top oxide cladding 212 and the bottom oxide cladding 214 (or BOX layer) (collectively, cladding 212, 214) extend along or substantially along the longitudinal direction. The cladding 212, 214 includes at least two regions: an inner cladding 222 which is defined between the two longitudinal rows of periodic trenches and provides the suspended waveguide 202, and an outer cladding 224 which is spaced apart from the inner cladding 222 by periodically-arranged lateral support rods 206 and provides support for the suspended waveguide 202. The inner cladding 222 and the outer cladding 224 are interconnected by the lateral support rods 206.

[034] A lateral support rod 206 is arranged or interposed between adjacent trenches 204. Each support rod 206 extends in the lateral direction and interconnects the suspended waveguide 202 and the outer cladding 224. Accordingly, a plurality of lateral support rods 206 respectively arranged or interposed between the isolation trenches 204 interconnect the waveguide 202 and the outer cladding 224 to provide mechanical support to the waveguide 202 which is suspended. Each support rod 206 has opposed ends, e.g., a first end and a second end, wherein the first end is attached to the suspended waveguide 202 (or inner cladding 222) and includes a first edge width w_1 interfacing the suspended waveguide 202, and wherein the second end is attached to the outer cladding 224 and includes a second edge width w_2 interfacing the outer cladding 224. Each support rod 206 has a footprint (see FIG. 2D) which at least includes the first edge width w_1 and the second edge width w_2 . The second edge width w_2 is larger than the first edge width w_1 . In other words, the first edge width w_1 is narrower than the second edge width w_2 . The first edge width w_1 is located more proximate to the waveguide and may be as narrow as possible to prevent mode perturbation while the second edge width w_2 is wider than the first edge width w_1 to improve mechanical rigidity and reliability of the edge coupler structure. The footprint may further include a third edge width w_3 and a fourth edge width w_4 respectively interfacing adjacent ones of the trenches 206. In the present disclosure, the term "footprint" includes references to an area taken from a plan view.

[035] The substrate 216 is provided with a cavity 218. The cavity 218 is in fluid communication with the isolation trenches 204. The waveguide 202 is suspended over the cavity 218 and supported by the support rods 206 arranged at the opposed

sidewalls of the waveguide 202. The support rods 206 interconnect the waveguide 202 and the outer cladding 224. At least a portion of the outer cladding 224 is unsuspended, e.g., supported by the substrate 216.

[036] An inverse taper 208, which may be part of an inversely tapered or second waveguide 210, is embedded in the suspended waveguide 202 and extends at most partially therewithin along the longitudinal direction, particularly from an intermediate position between the first end and the second end of the waveguide 202 towards the second end of the waveguide 202. The inverse taper 208 is narrower at the intermediate position and wider at the second end of the waveguide 202. As light propagates from the intermediate position towards the second end of the waveguide 202, the taper 208 facilitates adiabatic coupling of light from the suspended waveguide 202 into the inversely tapered waveguide 210 coupled thereto.

[037] In some embodiments, the suspended waveguide 202, cladding 212, 214, and support rods 206 are constructed from silicon oxide. The substrate 216, and the inverse taper 208 are constructed from silicon. The trenches 204 and the cavity 218 comprise air. In other embodiments, the inverse taper 208 may be constructed from silicon nitride (SiN), aluminium nitride (AlN), or any other material which has higher refractive index than the first waveguide 202.

[038] In some embodiments (see FIGs. 2A to 2D), the footprint of each support rod 206 includes an isosceles trapezoid. In the present disclosure, an isosceles trapezoid is generally understood as a quadrilateral having two parallel sides of unequal dimensions or lengths and two non-parallel sides of equal dimensions or length. Particularly, in such embodiments, the first edge width w_1 and the second edge width w_2 of the outline correspond to the two parallel sides of unequal dimensions or lengths, while the third edge width w_3 and the fourth edge width w_4 of the outline correspond to the two non-parallel sides of equal dimension or length.

[039] In some embodiments, the outline of each support rod 206 includes a trapezoid. In the present disclosure, a trapezoid is generally understood as a quadrilateral having two parallel sides of unequal equal dimensions or lengths and two non-parallel sides

of unequal equal dimensions or lengths. Particularly, in such embodiments, the first edge width w_1 and the second edge width w_2 of the outline correspond to the two parallel sides of unequal dimensions or lengths, while the third edge width w_3 and the fourth edge width w_4 of the outline correspond to the two non-parallel sides of unequal dimensions or lengths.

[040] In some embodiments (see FIGs. 3A and 3B), the outline of each support rod 206 includes a plurality of juxtaposed or stacked rectangles of different dimensions or lengths, e.g., two rectangles of different lengths, three rectangles of different lengths, etc.

[041] In some embodiments (see FIGs. 3C and 3D), the third edge w_3 and/or the fourth edge w_4 include an arc of a circle, an ellipse, a parabola, or a hyperbola. The third edge w_3 and the fourth edge w_4 , selected from one or more of the above examples, may be symmetrical or asymmetrical relative to each other.

[042] In some embodiments, the third edge w_3 and the fourth edge w_4 may be symmetrical or asymmetrical relative to each other.

[043] In some embodiments, the second edge width w_2 may be multiples of the first edge width w_1 . A ratio of the first edge width w_1 to the second edge width w_2 may be configured to provide an angle, between the third edge and an edge of the one of the isolation trenches which is adjacent to the first edge width w_1 , which is more than 45 degrees.

[044] FIG. 2D shows an isosceles trapezoid footprint of a support rod with the following parameters:

w_1 = first edge width

w_2 = second edge width

w_3 = third edge width

w_4 = fourth edge width

α = angle is between the third edge and an edge of the one of the trenches which is adjacent to the first edge width

h = dimension of each or a trench adjacent to the first edge width w_1 and the second edge width w_2 , and taken in the lateral direction (or referred to as “lateral dimension”)

$2d$ = difference between the second edge width w_2 and the first edge width w_1 . Accordingly, relations among the aforementioned parameters may be represented as follows:

$$\begin{aligned} w_2 &= 2d + w_1 \\ d &= 0.5(w_2 - w_1) \\ \tan \alpha &= \frac{h}{0.5(w_2 - w_1)} \\ \alpha &= \arctan \frac{h}{d} \end{aligned}$$

[045] If a designed value of angle α is very small or sharp, etchant cannot penetrate sharp corners during fabricating, which will result in rounding effects at those corners. The rounding effects will cause the fabricated edge widths of the support rods to be larger than the designed edge widths.

[046] In some embodiments, an angle α which is more than 45 degrees is to be provided. Accordingly, the first edge width w_1 , the second edge width w_2 , and the lateral dimension of each trench h are based on the following relation:

$$\arctan \left(\frac{h}{0.5(w_2 - w_1)} \right) > 45^\circ$$

[047] It is to be appreciated that other values of angle α , e.g., 90 degrees, may be envisaged.

[048] It is to be appreciated that the above parameters and relations apply to footprints of other shapes with suitable adaptations.

[049] FIG. 4 shows the measured optical loss spectrums measured at C-band for a conventional suspended edge coupler with rectangular support rod design where $w_1 = w_2 = 2 \mu\text{m}$, and one of the embodiments where the isosceles trapezoid oxide support rod design has design parameters of $w_1 = 2 \mu\text{m}$ and $w_2 = 10 \mu\text{m}$. Compared to the conventional design, the embodiment of the present disclosure does not induce any excess coupling loss, indicating that it does not perturb the light propagation through the suspended oxide waveguide, e.g., optical field does not leak into the support rods.

Accordingly, embodiments of the present disclosure provide suspended edge coupler designs that improve mechanical rigidity of edge couplers without deteriorating their coupling performance.

[050] Various methods of fabricating suspended edge couplers may be envisaged. In some embodiments, a method for fabricating a suspended edge coupler includes: producing a silicon-on-insulator (SOI) structure in which a silicon layer is formed on a buried oxide (BOX) layer which is formed on a silicon substrate. The method further includes: forming a top cladding on the SOI structure. The method further includes: pattern etching the top cladding and the SOI structure with two longitudinal rows of periodic isolation trenches to define an inner cladding between the two longitudinal rows of periodic isolation trenches, an outer cladding separated from the inner cladding by one of the two longitudinal rows of periodic isolation trenches, and lateral support rods interconnecting the inner cladding and the outer cladding. This pattern etching step may be performed without etching the silicon substrate. The method further includes: isotropic etching the silicon substrate to cause suspension of the inner cladding to provide a suspended waveguide. In the aforesaid pattern etching step, it includes forming each support rod which includes a footprint having a first edge width interfacing the suspended waveguide, and a second edge width interfacing the outer cladding, wherein the second edge width is larger than the first edge width, and wherein the first waveguide includes an inverse taper of a second waveguide. Other features of the fabricated suspended waveguide have been described in the foregoing paragraphs in relation to the figures, hence a description of such features is not repeated.

[051] 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. An edge coupler comprising:
 - a suspended waveguide having a longitudinal direction and a lateral direction, the waveguide arranged between two longitudinal rows of periodic isolation trenches
 - an outer cladding;
 - a plurality of lateral support rods arranged between the isolation trenches and interconnecting the waveguide and the outer cladding;
 - a silicon substrate having a cavity in fluid communication with the isolation trenches, wherein the waveguide and the support rods are suspended over the cavity, wherein the outer cladding is supported by the substrate; and
 - an inverse taper of a second waveguide which is embedded in the suspended waveguide,wherein each support rod includes a footprint having a first edge width interfacing the waveguide, and a second edge width interfacing the cladding, wherein the second edge width is larger than the first edge width.
2. The edge coupler of claim 1, wherein the footprint of each support rod includes a trapezoid having two parallel sides of unequal dimensions corresponding to the first edge width and the second edge width.
3. The edge coupler of claim 2, wherein the trapezoid is an isosceles trapezoid.
4. The edge coupler of claim 1, wherein the footprint of each support rod includes a plurality of juxtaposed rectangles of different dimensions.
5. The edge coupler of claim 1, wherein the footprint of each support rod includes a third edge width and a fourth edge width interfacing adjacent ones of the isolation trenches, wherein the third edge and/or the fourth edge include an arc of a circle, an ellipse, a parabola, or a hyperbola.
6. The edge coupler of claim 1, wherein the footprint of each support rod includes a third edge width and a fourth edge width interfacing adjacent ones of the isolation

trenches, and wherein the third edge width and the fourth edge width are asymmetric relative to each other.

7. The edge coupler of any one of claim 1 to claim 6, wherein dimensions of the first edge width and the second edge width are based on

$$\arctan\left(\frac{h}{0.5(w_2 - w_1)}\right) > 45^\circ$$

wherein w_1 corresponds to the first edge width, w_2 corresponds to the second edge width, and h corresponds to a lateral dimension of a corresponding one of the isolation trenches which is adjacent the first edge width and the second edge width.

8. The edge coupler of any one of claim 1 to claim 7, wherein the suspended waveguide includes a lateral dimension which tapers along the longitudinal direction.

9. The edge coupler of any one of claim 1 to claim 8, wherein the isolation trenches include air.

10. A method for fabricating an edge coupler, the method comprising:

forming a top cladding on a silicon-on-insulator (SOI) structure which includes a silicon layer which is formed on a buried oxide (BOX) layer which is formed on a silicon substrate;

without etching the silicon substrate, pattern etching the top cladding and the SOI structure with two longitudinal rows of periodic isolation trenches to define an inner cladding between the two longitudinal rows of periodic isolation trenches, an outer cladding separated from the inner cladding by one of the two longitudinal rows of periodic isolation trenches, and lateral support rods interconnecting the inner cladding and the outer cladding;

isotropic etching the silicon substrate to cause suspension of the inner cladding to provide a suspended waveguide;

wherein each support rod includes a footprint having a first edge width interfacing the suspended waveguide, and a second edge width interfacing the outer cladding, wherein the second edge width is larger than the first edge width, and wherein the first waveguide includes an inverse taper of a second waveguide.

11. The method of claim 10, wherein the footprint of each support rod includes a trapezoid having two parallel sides of unequal dimensions corresponding to the first edge width and the second edge width.
12. The method of claim 11, wherein the trapezoid is an isosceles trapezoid.
13. The method of claim 10, wherein the footprint of each support rod includes a plurality of juxtaposed rectangles of different dimensions.
14. The method of claim 10, wherein the footprint of each support rod includes a third edge width and a fourth edge width interfacing adjacent ones of the isolation trenches, wherein the third edge and/or the fourth edge include an arc of a circle, an ellipse, a parabola, or a hyperbola.
15. The method of claim 10, wherein the footprint of each support rod includes a third edge width and a fourth edge width interfacing adjacent ones of the isolation trenches, and wherein the third edge width and the fourth edge width are asymmetric relative to each other.
16. The method of any one of claim 10 to claim 15, wherein dimensions of the first edge width and the second edge width are based on
- $$\arctan\left(\frac{h}{0.5(w_2 - w_1)}\right) > 45^\circ$$
- wherein w_1 corresponds to the first edge width, w_2 corresponds to the second edge width, and h corresponds to a lateral dimension of a corresponding one of the isolation trenches which is adjacent the first edge width and the second edge width.
17. The method of any one of claim 10 to claim 16, wherein the suspended waveguide includes a lateral dimension which tapers along the longitudinal direction.
18. The method of any one of claim 10 to claim 17, wherein the isolation trenches include air.