

PHOTONIC INTEGRATED CIRCUIT HAVING A WAVEGUIDE-GRATING COUPLER

BACKGROUND

5 Field of the Invention

The present invention generally relates to optical communication equipment and, more specifically but not exclusively, to optical devices for coupling light into and out of photonic integrated circuits.

10 Description of the Related Art

This section introduces aspects that may help facilitate a better understanding of the invention(s). Accordingly, the statements of this section are to be read in this light and are not to be understood as admissions about what is in the prior art or what is not in the prior art.

15 Photonic integrated circuits (PICs) are used for various applications in telecommunications, instrumentation, and signal-processing fields. A PIC typically uses optical waveguides to implement and/or interconnect various on-chip components, such as optical switches, couplers, routers, splitters, multiplexers/demultiplexers, modulators, amplifiers, wavelength converters, optical-
20 to-electrical (O/E) and electrical-to-optical (E/O) signal converters, etc. A waveguide in a PIC is usually an on-chip solid light conductor that guides light due to an index-of-refraction contrast between the waveguide's core and cladding.

For proper operation, a PIC typically needs to efficiently couple light between an external optical fiber and one or more of on-chip waveguides. An exemplary
25 grating coupler that can be used for this purpose is disclosed, e.g., in U.S. Patent No. 7,065,272, which is incorporated herein by reference in its entirety. However, one problem with some grating couplers is that they work well only when implemented using materials that provide a relatively high index-of-refraction contrast between the core and both the upper and lower cladding layers, whereas certain active optical
30 elements of the PIC require the use of materials that can provide only a relatively low index-of-refraction contrast.

SUMMARY

Advantageously, some embodiments of the waveguide-grating couplers disclosed herein do not have low light-coupling efficiencies of prior-art waveguide-grating couplers and are convenient for integration into photonic integrated circuits (PICs) having III-V semiconductor-based active optical elements. In particular, problems of the prior art are addressed by providing a waveguide-grating coupler having two evanescently coupled waveguides. The first waveguide is fabricated using materials suitable for manufacturing active optical elements, and the second waveguide is fabricated using materials capable of providing a relatively high index-of-refraction contrast for the constituent waveguide grating.

According to one embodiment, provided is an apparatus having (i) a first optical waveguide being supported on a surface of a substrate; (ii) a second optical waveguide being supported over the surface; (iii) an optical coupler being supported over the surface and optically coupling the first and second waveguides; and (iv) a waveguide grating being supported over the surface and being adapted to transfer optical power between one or more waveguide modes of the second waveguide and an optical beam formed by or applied to the waveguide grating. The second waveguide has an offset-transition region for which a core of the second waveguide has an offset distance that gradually changes from a first distance corresponding to the coupler to a different second distance.

In various additional embodiments, the apparatus may have one or more of the following features: (a) at least one of the core and a cladding of the second waveguide comprises a material that is different from materials in a core and a cladding of the first waveguide; (b) the substrate forms a cladding of the first waveguide.

According to another embodiment, provided is a photonic integrated circuit (PIC) having (i) a substrate; (ii) an optical signal-processing (OSP) circuit being supported on the substrate and having at least one active optical element; (iii) a first optical waveguide being optically coupled to the active optical element; (iv) a second optical waveguide having a waveguide grating adapted to transfer optical power between one or more waveguide modes of the second optical waveguide and an optical beam formed by or applied to the waveguide grating; and (v) an optical

coupler that couples the first and second waveguides only via evanescent fields. The second optical waveguide has an offset-transition region, within which a core of the second optical waveguide has an offset distance with respect to the substrate that gradually changes from a first distance to a different second distance.

- 5 According to yet another embodiment, provided is a method of fabricating an optical device having the steps of: (A) providing a substrate having a first optical waveguide thereon, the first optical waveguide having a cladding layer with a wedge-like portion; (B) forming a core of a second optical waveguide on the wedge-like portion and an exposed portion of the cladding of the first waveguide; and
- 10 (C) forming an array of cavities in the core of the second optical waveguide to define therein a waveguide grating.

- In various additional embodiments, the method may have an additional step of forming on the substrate an OSP circuit, with one or more of the following features:
- 15 (a) the first optical waveguide is optically coupled to the OSP circuit; (b) the OSP circuit comprises at least one active optical element; (c) the first and second optical waveguides, the waveguide grating, and the OSP circuit are parts of a photonic integrated circuit (PIC) formed on the substrate; (d) a core of the first optical waveguide comprises a ternary, quaternary, or quinary group III-V alloy; (e) a cladding of the first waveguide comprises a binary group III-V compound; (f) the core
- 20 of the second waveguide comprises silicon; (g) the wedge-like portion comprises silicon oxide; and (h) for a specified operating wavelength, an offset distance between the waveguide grating and an interface of a cladding of the first optical waveguide with a cladding of the second waveguide is selected to cause constructive interference between (i) light of said wavelength diffracted by the waveguide grating toward the
- 25 interface and then reflected back by the interface and (ii) light of said wavelength diffracted by the waveguide grating in a direction collinear with a propagation direction of the reflected light.

BRIEF DESCRIPTION OF THE DRAWINGS

- 30 Other aspects, features, and benefits of various embodiments of the invention will become more fully apparent, by way of example, from the following detailed description and the accompanying drawings, in which:

Fig. 1 shows a top view of a photonic integrated circuit (PIC) according to one embodiment of the invention;

Figs. 2A-C show cross-sectional side views of an optical coupler that can be used in the PIC of Fig. 1 according to one embodiment of the invention;

5 Figs. 3A-B show top views of two representative patterns that can be used in the waveguide grating of the optical coupler shown in Fig. 2 according to some embodiments of the invention; and

Fig. 4 shows a flowchart of a fabrication method that can be used to manufacture the optical coupler of Fig. 2 according to one embodiment of the
10 invention

DETAILED DESCRIPTION

Fig. 1 shows a top view of a photonic integrated circuit (PIC) **100** according to one embodiment of the invention. PIC **100** is a substantially planar monolithic
15 device, whose lateral dimensions (e.g., dimensions within the plane of Fig. 1) are significantly larger than the transverse dimension (e.g., the height or thickness along the axis orthogonal to the plane of Fig. 1). PIC **100** is illustratively shown as having two optical couplers **110a-b** and one optical signal-processing (OSP) portion or circuit **120**, although a PIC with a different number of optical couplers and/or OSP
20 portions is also possible. In a typical embodiment, couplers **110a-b** and OSP portion **120** are implemented on and supported by a common substrate **102**.

In a representative configuration of PIC **100**, a first external optical fiber (not explicitly shown) oriented approximately orthogonally with respect to the plane of Fig. 1 applies an unguided incoming beam of light to coupler **110a**. As used herein,
25 the term “unguided” refers to an optical beam that is not laterally confined by a light-guiding structure, such as an on-chip waveguide or an optical fiber. Due to a finite spatial separation between the tip of the external optical fiber and coupler **110a**, the optical beam impinging upon the coupler is an unguided optical beam. Coupler **110a** couples the light of the received optical beam, through a waveguide taper **112a**, into a
30 planar waveguide **118a**. Waveguide **118a** then delivers the coupled light to OSP portion **120**. OSP portion **120** processes the light using one or more optical elements located therein and applies the resulting light to a planar waveguide **118b**, which then

directs that light, through a waveguide taper **112b**, to coupler **110b**. Coupler **110b** forms an outgoing unguided optical beam, which is coupled into a second external optical fiber (not explicitly shown) oriented approximately orthogonally with respect to the plane of Fig. 1.

5 Structurally, coupler **110** comprises an evanescent coupler **130**, an offset-transition region **126**, and a waveguide grating **140**. Evanescent coupler **130** couples light between waveguide taper **112** and a second waveguide (not explicitly shown in Fig. 1) that is an internal element of coupler **110**. Offset-transition region **126** serves to gradually decrease the evanescent coupling at one of the edges of evanescent
10 coupler **130**. Waveguide grating **140** serves to transfer optical power between one or more waveguide modes of the second waveguide and an unguided optical beam formed by or applied to the waveguide grating. Representative embodiments of evanescent coupler **130**, offset-transition region **126**, and waveguide grating **140** are described in more detail below in reference to Figs. 2 and 3.

15 In a representative embodiment, OSP portion **120** comprises one or more active optical components, such as a semiconductor optical amplifier, a laser diode, and/or an optical modulator. These one or more active optical components are implemented, as known in the art, using III-V semiconductor materials, such as binary III-V compounds and/or ternary, quaternary, or quinary III-V alloys. While the III-V
20 semiconductor compounds and alloys offer well-known advantages for the implementation of active optical components, they can provide only a modest index-of-refraction contrast between the core and cladding materials. For example, in an InP-platform technology, the indices of refraction of the core and cladding materials are about 3.5 and 3.17, respectively, which produces an index-of-refraction contrast of
25 about 0.09. If a prior-art optical-coupler design were used to implement optical couplers **110a-b**, then, disadvantageously, either the light-coupling efficiency would be relatively low or the fabrication process would be too complicated and/or expensive, or both. In contrast, optical coupler **110** advantageously provides a relatively high light coupling efficiency (e.g., greater than about 35%) while being
30 relatively easy to fabricate on an industrial scale.

Figs. 2A-C show cross-sectional side views of an optical coupler **200** that can be used as optical coupler **110** according to one embodiment of the invention. More

specifically, Fig. 2A shows a full cross-sectional side view of coupler **200**. Fig. 2B shows an enlarged cross-sectional side view of a structure **230** for evanescently coupling light between waveguides **210** and **220** in coupler **200**. Fig. 2C shows an enlarged cross-sectional side view of a waveguide grating **240** used in coupler **200**.

- 5 In the description that follows, the operation of coupler **200** is illustratively explained in reference to a process of coupling light out of the corresponding PIC. From this description, one of ordinary skill in the art will readily understand the operation of coupler **200** in a process of coupling light into the PIC.

Optical coupler **200** has two waveguides **210** and **220** that are evanescently
10 coupled to one another via structure **230** (see Figs. 2A and 2B). Waveguide **210** is optically coupled to and configured to receive light from an OSP portion of the corresponding PIC, e.g., as indicated in Fig. 1. Structurally, waveguide **210** comprises (i) a core layer **204** of a high-index material and (ii) two cladding layers **202** and **206** of low-index material(s) that are adjacent to the core layer. In one
15 embodiment, cladding layer **202** is a substrate layer, which also serves as a substrate for the OSP portion of the PIC and is analogous to substrate **102** of PIC **100** (Fig. 1). Exemplary materials for substrate **202** and cladding layer **206** are InP, GaN, sapphire, InAs, and GaAs. Note that substrate **202** and cladding layer **206** can be made of the same material or different materials. Exemplary materials for core layer **204** are
20 ternary GaInAs, quaternary GaInAsP, and quaternary AlGaInAs.

Waveguide **220** has (i) a core layer **214** of a high-index material and (ii) two cladding layers **212** and **216** of low-index material(s). Exemplary materials for core layer **214** are amorphous silicon and polycrystalline silicon. Exemplary materials for cladding layers **212/216** are silicon oxide and silicon oxynitride. Note that, similar to
25 substrate **202** and cladding layer **206**, cladding layers **212/216** can be made of the same material or different materials.

Waveguide **220** has an offset-transition region **226**, wherein the vertical separation between core layer **204** of waveguide **210** and core layer **214** of waveguide **220** is not constant. Herein, the term “vertical” refers to the Z-coordinate axis, which
30 is orthogonal to the principal (XY) plane of the PIC defined by the principal plane of the substrate, e.g., substrate **102** (Fig. 1) or substrate **202** (Fig. 2). A first portion **214₁** of core layer **214** is directly adjacent to cladding layer **206** and is generally parallel to

the XY plane (see Fig. 2B). A second portion **214₂** of core layer **214** is oriented at an angle with respect to the XY plane, which causes the vertical separation between core layers **204** and **214** to gradually increase from the left side to the right side of portion **214₂** (see Fig. 2A). In a typical embodiment, the angle between portion **214₂** and the
 5 XY plane is greater than about 3 degrees. A third portion **214₃** of core layer **214** is generally parallel to the XY plane and is connected to a waveguide grating **240** defined in core layer **214** (see Figs. 2A and 2C).

Referring to Fig. 2B, core-layer portion **214₁** and the underlying portions of cladding layer **206** and core layer **204** create structure **230**. Various parameters of
 10 waveguides **210** and **220**, such as the thicknesses and refractive indices of the various constituent layers, can be chosen so as to match the two waveguides within structure **230** in terms of their propagation constants. With waveguides **210** and **220** having substantially equal propagation constants, evanescent light coupling between core layers **204** and **214** in structure **230** will cause the optical energy initially confined in
 15 one waveguide to substantially fully transfer into the other waveguide over a distance (Λ) expressed by Eq. (1):

$$\Lambda = \frac{\pi}{\beta_e - \beta_o} \quad (1)$$

where β_e and β_o are the even and odd propagation constants, respectively, of the matched waveguides.

20 Suppose now that an optical signal (e.g., received from OSP portion **120**, Fig. 1) is initially confined in waveguide **210** and propagates from the left side of Fig. 2A toward structure **230**. If the X dimension of structure **230** (labeled L in Fig. 2B) is chosen to be $(2m+1)\Lambda$, where m is zero or a positive integer, then, at the right side of structure **230** in Figs. 2A and 2B, the optical signal will be primarily confined in
 25 waveguide **220**. As the optical signal enters core-layer portion **214₂**, the increased separation between core layers **204** and **214** disrupts the evanescent coupling between waveguides **210** and **220** and causes the optical signal to remain confined in waveguide **220** thereafter.

Note that, for positive m values, the energy of the optical signal spatially beats
 30 m times between waveguides **210** and **220** within structure **230** before waveguide **220** separates sufficiently from waveguide **210** to disrupt the evanescent coupling between

the waveguides at the right side of the structure. As used herein, the term “one spatial beat” refers to a spatial process of changing the optical power distribution, e.g., from a state of being primarily confined to waveguide **210** to a state of being primarily confined to waveguide **220** and then back to waveguide **210**. A representative

5 threshold value that can be used to delimit the power-redistribution process is, e.g., 80% of the total optical power contained within a transverse (YZ) cross-section of structure **230**. Using this threshold value, it can be said that the optical power is primarily confined to one of the waveguides when the waveguide mode(s) corresponding to that waveguide contain about 80% of the total optical power within

10 the transverse cross-section.

Core-layer portions **214₂** and **214₃** of waveguide **220** direct the optical signal from structure **230** to waveguide grating **240**. In a representative embodiment, waveguide grating **240** comprises a plurality of cavities, pillars, and/or holes etched into or formed on an upper surface of core layer **214** to form a one- or two-

15 dimensional pattern (see Figs. 2A and 2C). This pattern causes the power of the optical signal to be diffracted vertically from waveguide grating **240**, both in the positive and negative Z directions. A representative grating that can be used as waveguide grating **240** is disclosed, e.g., in the above-cited U.S. Patent No. 7,065,272.

20 In an exemplary embodiment, core layer **214** is made of silicon, and cladding layers **212/216** are made of silicon oxide. This combination of materials enables waveguide grating **240** to have a relatively high index-of-refraction contrast between the core and both the upper and lower cladding layers, e.g., about 0.57, for core and cladding indices of about 3.5 and 1.5, respectively. As already indicated above, a

25 high index-of-refraction contrast is advantageous in that it enables waveguide grating **240** to provide efficient energy transfer between the waveguide modes of waveguide **220** and the unguided vertical optical beams formed or received by the waveguide grating. In other words, a relatively “strong” grating is employed to diffract much of the light in a relatively short distance, e.g., the distance equal to the fiber mode width,

30 which is achieved, e.g., by having a very low upper-cladding index with respect to the core index. Such a “strong” grating reduces the effective index of the core and, thus,

for the light to still be guided by the core in the grating region, the lower cladding is implemented with a very low index with respect to the core index.

The light diffracted by waveguide grating **240** in the negative Z direction impinges on and is partially reflected by an interface **211** between cladding layers **206** and **212** (see Figs. 2A and 2C). The reflected light then interferes with the light
 5 diffracted by waveguide grating **240** in the positive Z direction. In one embodiment, the thickness of cladding layer **212** underneath waveguide grating **240** is chosen so that the light reflected off interface **211** interferes constructively with the light
 10 diffracted by the waveguide grating in the positive Z direction. The constructive interference is advantageous in that it improves the coupling efficiency between the PIC having optical coupler **200** and an external optical fiber positioned next to the upper (in the projection of Fig. 2A) side of the coupler near waveguide grating **240**.

Eq. (2) provides guidance for selecting (i) the thickness of cladding layer **212** underneath waveguide grating **240** and (ii) certain parameters of the waveguide
 15 grating:

$$L_s n_s + L_{eff} n_g = p \frac{\lambda}{2} \quad (2)$$

where L_s and n_s are the thickness and refractive index, respectively, of cladding layer **212**; L_{eff} is the effective distance between interface **211** and waveguide grating **240**; n_g is the refractive index of core layer **214** in waveguide grating **240**; λ is the wavelength
 20 of light; and p is a positive integer. The dimensions corresponding to L_s and L_{eff} are marked in Fig. 2C.

The energy-transfer efficiency of grating **240** can be optimized for any selected wavelength or a range or wavelengths by using a corresponding appropriate pattern of cavities, grooves, or holes. For example, the above-cited U.S. Patent No.
 25 7,065,272 discloses patterns that can be used for efficiently coupling light having wavelengths between about 1500 nm and about 1600 nm. One skilled in the art will appreciate that, to obtain a waveguide grating suitable for efficient coupling of other wavelengths, the disclosed patterns can be modified, e.g., by appropriately changing the periodicity of cavities in the grating.

30 Figs. 3A-B show top views of patterns **340** and **350**, respectively, which can be used in waveguide grating **240** according to some embodiments of the invention.

Pattern **340** (Fig. 3A) comprises a plurality of holes **344** arranged in rows in a rectangular configuration. Pattern **350** (Fig. 3B) comprises a plurality of parallel grooves **354**. The pitch of each pattern along the X direction is approximately λ/n , where n is the refractive index of the grating material. In one embodiment, the depth of holes **344** and grooves **354** is between about 100 nm and about 200 nm. The diameter of holes **344** and the width of grooves **354** are between about 40% and 60% of the pitch.

Numerical simulations of optical coupler **200** (Fig. 2A) having waveguide-grating pattern **350** (Fig. 3B) indicate that the optical coupler can provide a coupling efficiency between waveguide **210** and an external optical fiber of about 35%. Representative characteristics of the various components of the optical coupler used in the numerical simulations are as follows: (i) GaInAsP core layer **204** having a refractive index of about 3.388 and a thickness of about 200 nm; (ii) InP cladding layers **202/206** having a refractive index of about 3.17; (iii) amorphous-silicon core layer **214** having a refractive index of about 3.48 and a thickness of about 400 nm; and (iv) silicon-oxide cladding layers **212/216** having a refractive index of about 1.58. The vertical separation between core layers **204** and **214** within structure **230** is 200 nm, which results in a half-beat distance Λ of about 10.5 μm (see also Eq. (1)). The thickness of cladding layer **212** underneath waveguide grating **240** is about 700 nm.

Fig. 4 shows a flowchart of a fabrication method **400** that can be used to manufacture optical coupler **200** according to one embodiment of the invention. As evident from the description that follows, method **400** is readily amenable to high-volume industrial production. In contrast, a typical prior-art method for fabricating an optical coupler with a coupling efficiency comparable to that of optical coupler **200** is rather complicated and is not suitable for high-volume industrial production, e.g., because it involves a step of flip-chip bonding two separate preprocessed wafers, one corresponding to the active portion of the PIC and the other to the waveguide grating.

At step **402** of method **400**, waveguide **210** is formed by (i) depositing or growing core layer **204** on substrate **202**; (ii) patterning and etching core layer **204** using lithographic methods to form a desired footprint layout for waveguide **210**; and (iii) depositing or growing cladding layer **206** over core layer **204** and substrate **202**

(see Fig. 2A). Note that the processing of sub-step (ii) can be at least partially performed concurrently with step **410**.

At step **404**, wedged cladding layer **212** is formed over cladding layer **206** (see Fig. 2A). At a first sub-step of step **404**, initial cladding layer **212** is deposited or
5 grown on cladding layer **206** so that the layer extends across the entire width of the nascent coupler, e.g., from the left side to the right side of Fig. 2A. At a second sub-step of step **404**, part of cladding layer **212** corresponding to core-layer portion **214₃** and waveguide grating **240** is masked off, and the resulting structure is subjected to wet-etch processing. Since silicon oxide (a typical material for implementing
10 cladding layer **212**) is an amorphous material, it etches in a substantially isotropic manner, thereby creating a naturally sloped wall near the edge of the mask. This sloped wall becomes the wedged portion of cladding layer **212** located beneath core-layer portion **214₂** in Fig. 2A. The angle of the wedge is a function of the vertical etch rate and the lateral etch rate, both of which are controlled by the chemical
15 composition of the etchant and the temperature at which the wet etch is carried out. Cladding layer **206** serves as an etch stop in the unmasked portion of the structure. After the wet etch is completed, the mask is stripped off.

At step **406**, core layer **214** is deposited over wedged cladding layer **212** and the exposed part of cladding layer **206**. A suitable deposition method for step **406** is
20 plasma-enhanced chemical vapor deposition or electron-beam evaporation. The vertical profile of core layer **214** generally conforms to the topology of its base layers, i.e., cladding layers **212** and **206**. Deposited core layer **214** is then patterned and etched using lithographic methods to form desired footprint layouts for waveguide **220** and evanescent coupler **230**.

25 At step **408**, core layer **214** produced at step **406** is patterned and etched in the portion corresponding to waveguide grating **240** to form cavities, holes, and/or grooves that define the grating.

At step **410**, cladding layer **216** is deposited over the structure produced at step **408**. The outer surface of cladding layer **216** is polished and optionally covered by an
30 anti-reflection coating to create the final structure of optical coupler **200** shown in Fig. 2A.

As used in this specification, the term “index-of-refraction contrast” refers to a value obtained by dividing the difference between the refractive indices of the core and the cladding by the refractive index of the core.

The present invention may be embodied in other specific apparatus and/or methods. The described embodiments are to be considered in all respects as only illustrative and not restrictive. In particular, the scope of the invention is indicated by the appended claims rather than by the description and figures herein. All changes that come within the meaning and range of equivalency of the claims are to be embraced within their scope. For example, various optical devices can be implemented as corresponding monolithic PICs, including implementations as substantially planar receiver cards or circuits.

The description and drawings merely illustrate the principles of the invention. It will thus be appreciated that those of ordinary skill in the art will be able to devise various arrangements that, although not explicitly described or shown herein, embody the principles of the invention and are included within its spirit and scope. Furthermore, all examples recited herein are principally intended expressly to be only for pedagogical purposes to aid the reader in understanding the principles of the invention and the concepts contributed by the inventor(s) to furthering the art, and are to be construed as being without limitation to such specifically recited examples and conditions. Moreover, all statements herein reciting principles, aspects, and embodiments of the invention, as well as specific examples thereof, are intended to encompass equivalents thereof.

Unless explicitly stated otherwise, each numerical value and range should be interpreted as being approximate as if the word “about” or “approximately” preceded the value or range.

It will be further understood that various changes in the details, materials, and arrangements of the parts which have been described and illustrated in order to explain the nature of this invention may be made by those skilled in the art without departing from the scope of the invention as expressed in the following claims.

Although the elements in the following method claims, if any, are recited in a particular sequence with corresponding labeling, unless the claim recitations otherwise imply a particular sequence for implementing some or all of those elements,

those elements are not necessarily intended to be limited to being implemented in that particular sequence.

Reference herein to “one embodiment” or “an embodiment” means that a particular feature, structure, or characteristic described in connection with the
5 embodiment can be included in at least one embodiment of the invention. The appearances of the phrase “in one embodiment” in various places in the specification are not necessarily all referring to the same embodiment, nor are separate or alternative embodiments necessarily mutually exclusive of other embodiments. The same applies to the term “implementation.”

10 Throughout the detailed description, the drawings, which are not to scale, are illustrative only and are used in order to explain, rather than limit the invention. The use of terms such as height, length, width, top, bottom, is strictly to facilitate the description of the invention and is not intended to limit the invention to a specific orientation. For example, height does not imply only a vertical rise limitation, but is
15 used to identify one of the three dimensions of a three dimensional structure as shown in the figures. Such “height” would be vertical where the electrodes are horizontal but would be horizontal where the electrodes are vertical, and so on. Similarly, while all figures show the different layers as horizontal layers such orientation is for descriptive purpose only and not to be construed as a limitation.

20 Also for purposes of this description, the terms “couple,” “coupling,” “coupled,” “connect,” “connecting,” or “connected” refer to any manner known in the art or later developed in which energy is allowed to be transferred between two or more elements, and the interposition of one or more additional elements is contemplated, although not required. Conversely, the terms “directly coupled,”
25 “directly connected,” etc., imply the absence of such additional elements.

CLAIMS

What is claimed is:

1. An apparatus, comprising:
 - a first optical waveguide being supported on a surface of a substrate;
 - 5 a second optical waveguide being supported over the surface;
 - an optical coupler being supported over the surface and optically coupling the first and second waveguides; and
 - a waveguide grating being supported over the surface and being adapted to transfer optical power between one or more waveguide modes of the second
 - 10 waveguide and an optical beam formed by or applied to the waveguide grating, wherein the second waveguide has an offset-transition region for which a core of the second waveguide has an offset distance that gradually changes from a first distance corresponding to the optical coupler to a different second distance.
- 15 2. The invention of claim 1, wherein:
 - a cladding of the second waveguide comprises a wedge-shaped portion located in the offset-transition region;
 - an index-of-refraction contrast of the second waveguide is greater than an index-of-refraction contrast of the first waveguide;
 - 20 a core of the first waveguide comprises a ternary, quaternary, or quinary group III-V alloy;
 - a cladding of the first waveguide comprises a binary group III-V compound;
 - the core of the second waveguide comprises silicon; and
 - the cladding of the second waveguide comprises silicon oxide.
- 25 3. The invention of claim 1, wherein the optical coupler couples the first and second optical waveguides via evanescent fields.
4. The invention of claim 3, wherein the optical coupler has a length that causes
- 30 optical energy to spatially beat one or more times between the first and second optical waveguides.

5. The invention of claim 1, wherein the core of the second optical waveguide comprises:

a first portion that is substantially parallel to a principal plane of the substrate;
a second portion located in the offset-transition region; and

5 a third portion that is substantially parallel to the principal plane, wherein:
the second portion is connected between the first and third portions; and
the waveguide grating is defined in the third portion.

6. The invention of claim 1, wherein the second offset distance is such that the
10 apparatus produces constructive interference between (i) light diffracted by the
waveguide grating toward an interface between a cladding of the first optical
waveguide and a cladding of the second optical waveguide and then reflected back by
the interface and (ii) light diffracted by the waveguide grating in a direction collinear
with a propagation direction of the reflected light.

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7. The invention of claim 1, wherein:

a core of first waveguide has a third offset distance with respect to the substrate;
and

the third offset distance is outside the range between the first distance and the
20 second distance.

8. The invention of claim 1, wherein:

a core of the first waveguide comprises a laterally tapered portion connected to the
optical coupler;

25 the apparatus further comprises an optical signal-processing (OSP) circuit
supported on the substrate, wherein the first waveguide is optically coupled to the
OSP circuit;

the OSP circuit comprises at least one active optical element; and

the first and second waveguides, the waveguide grating, and the OSP circuit are
30 parts of a photonic integrated circuit (PIC) formed on the substrate.

9. A photonic integrated circuit (PIC), comprising:

- a substrate;
- an optical signal-processing (OSP) circuit being supported on the substrate and having at least one active optical element;
- a first optical waveguide being optically coupled to the active optical element;
- 5 a second optical waveguide having a waveguide grating adapted to transfer optical power between one or more waveguide modes of the second optical waveguide and an optical beam formed by or applied to the waveguide grating; and
- an optical coupler that couples the first and second waveguides via evanescent fields, wherein the second optical waveguide has an offset-transition region, within
- 10 which a core of the second optical waveguide has an offset distance with respect to the substrate that gradually changes from a first distance to a different second distance.
10. A method of fabricating an optical device, comprising:
- 15 providing a substrate having a first optical waveguide thereon, the first optical waveguide having a cladding layer with a wedge-like portion;
- forming a core of a second optical waveguide on the wedge-like portion; and
- forming an array of cavities in the core of the second optical waveguide to define therein a waveguide grating, wherein the step of providing comprises:
- 20 forming a layer of cladding material over the first optical waveguide; and
- subjecting the layer to a wet-etch process to form from the layer the wedge-like portion.