US 20100304514A1

(19) **United States**

(12) **Patent Application Publication**

Block et al.

(10) **Pub. No.: US 2010/0304514 A1**

(43) **Pub. Date: Dec. 2, 2010**

(54) **EFFICIENT LIGHT COUPLER FROM OFF-CHIP TO ON-CHIP WAVEGUIDES**

(76) Inventors: **Bruce A. Block**, Portland, OR (US); **Paul Davids**, Portland, OR (US)

Correspondence Address:
INTEL/BSTZ
BLAKELY SOKOLOFF TAYLOR & ZAFMAN LLP
1279 OAKMEAD PARKWAY
SUNNYVALE, CA 94085-4040 (US)

(21) Appl. No.: **12/835,685**

(22) Filed: **Jul. 13, 2010**

Related U.S. Application Data

(60) Division of application No. 12/031,665, filed on Feb. 14, 2008, now Pat. No. 7,801,397, which is a continuation of application No. 10/421,640, filed on Apr. 22, 2003, now Pat. No. 7,343,058.

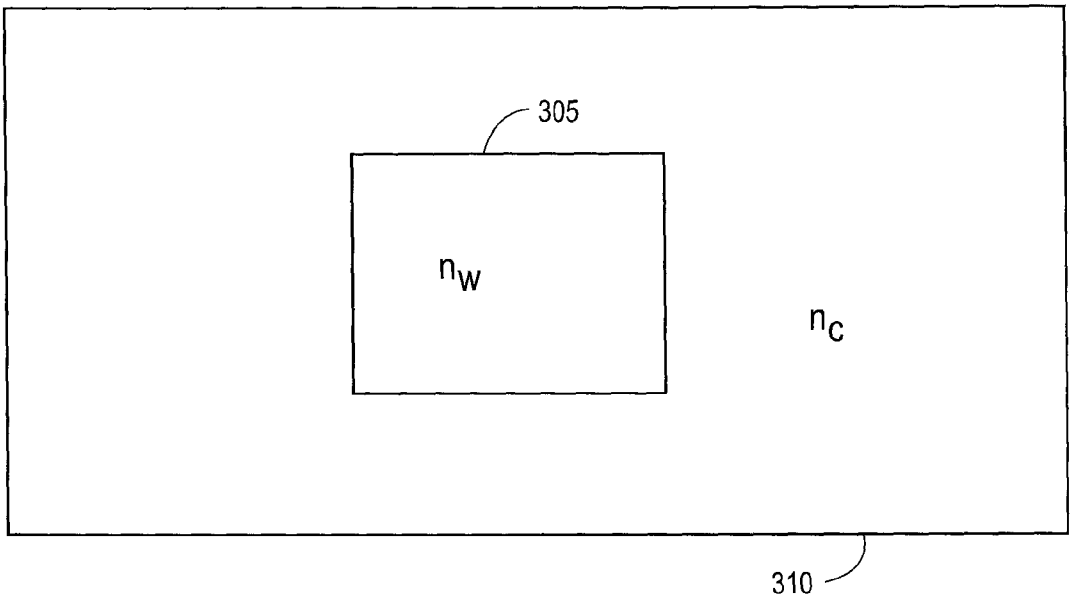
Publication Classification

(51) **Int. Cl.**
H01L 33/48 (2010.01)

(52) **U.S. Cl.** **438/27**; 257/E33.056

(57) **ABSTRACT**

In an embodiment, light from a single mode light source may be deflected into a low index contrast (LIC) waveguide in an opto-electronic integrated circuit (OEIC) (or "opto-electronic chip") by a 45 degree mirror. The mirror may be formed by polishing an edge of the die at a 45 degree angle and coating the polished edge with a metal layer. Light coupled into the LIC waveguide may then be transferred from the LIC waveguide to a high index contrast (HIC) waveguide by evanescent coupling.



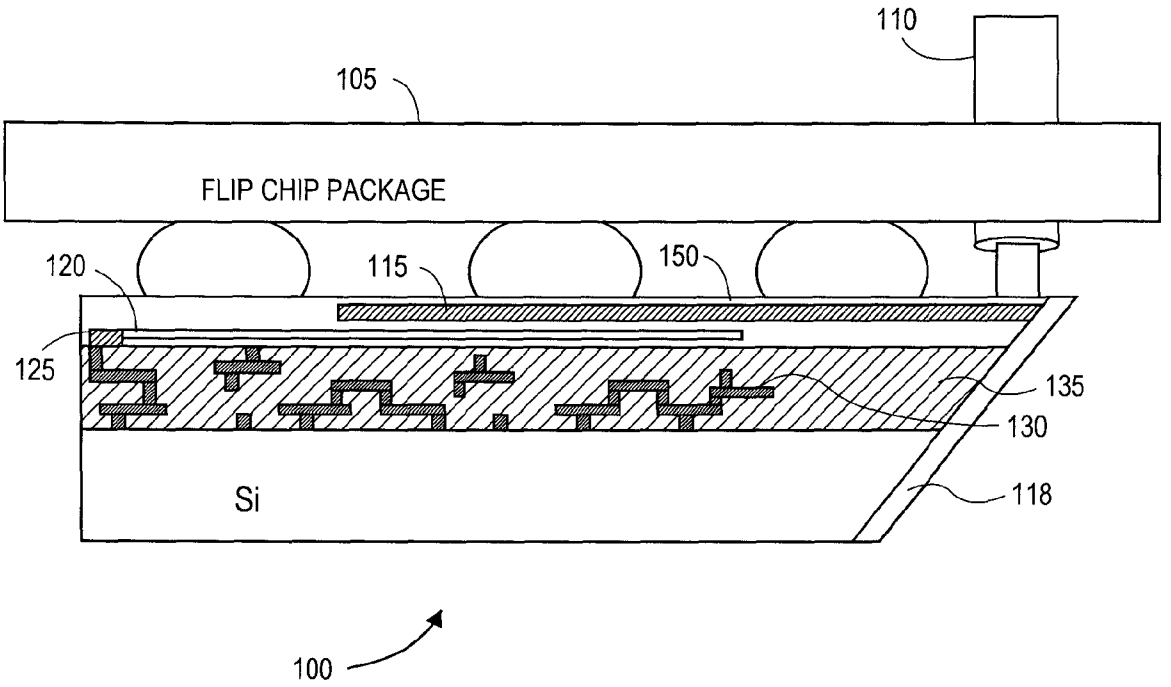


FIG. 1

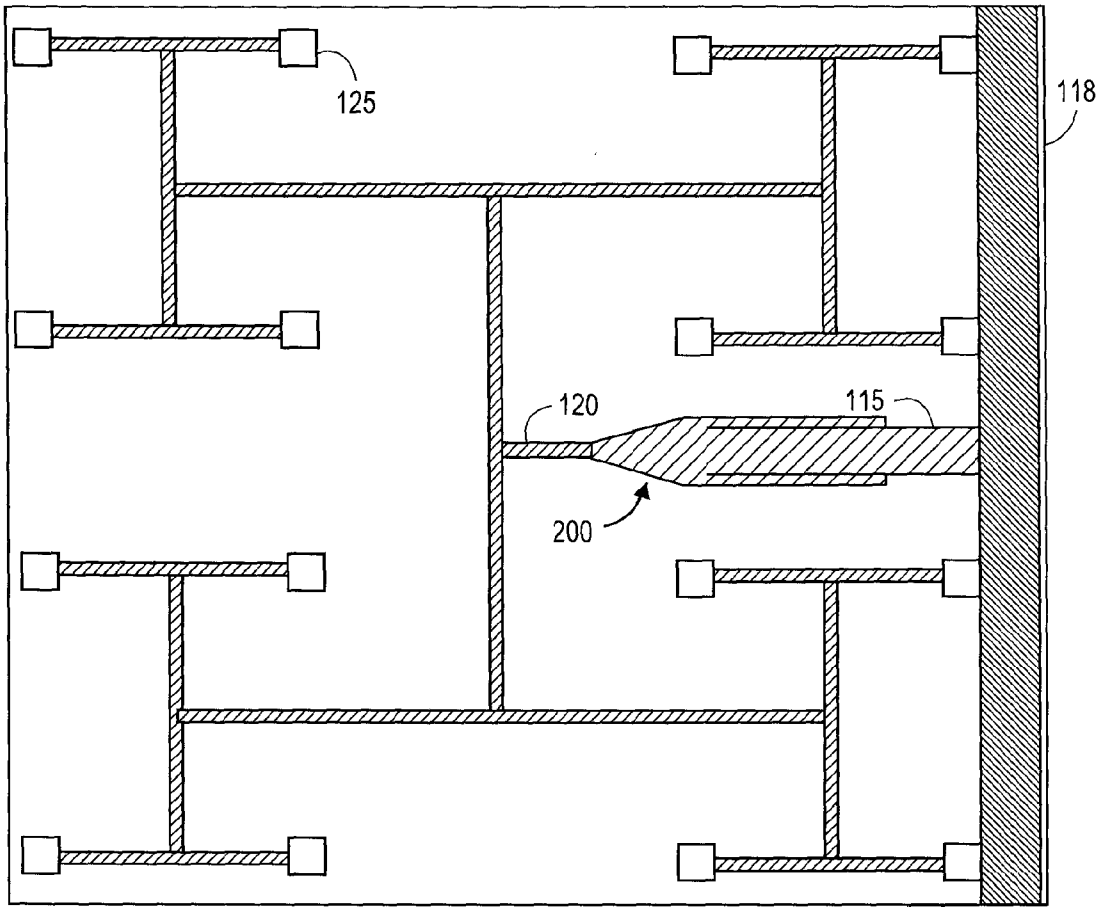


FIG. 2

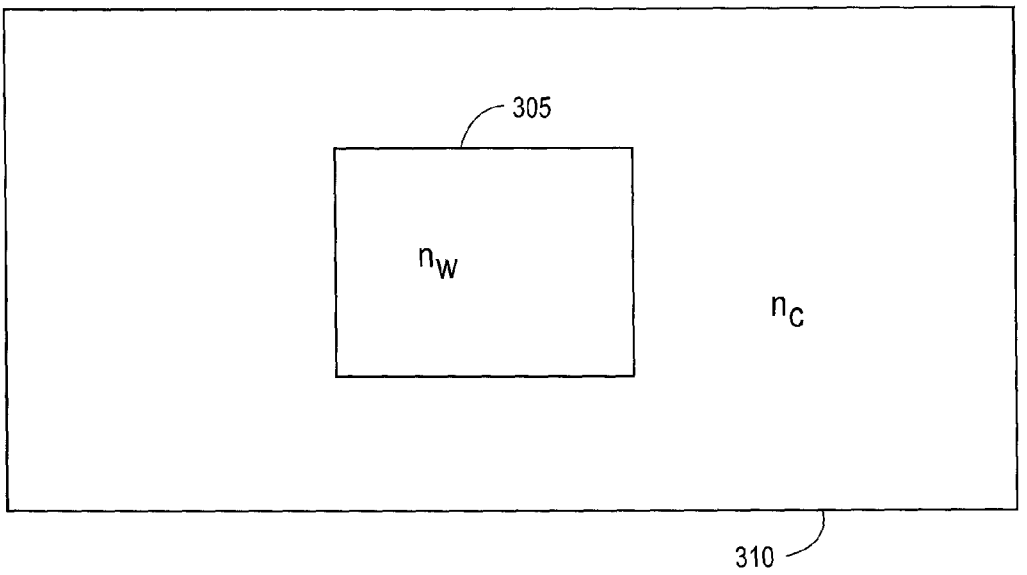


FIG. 3

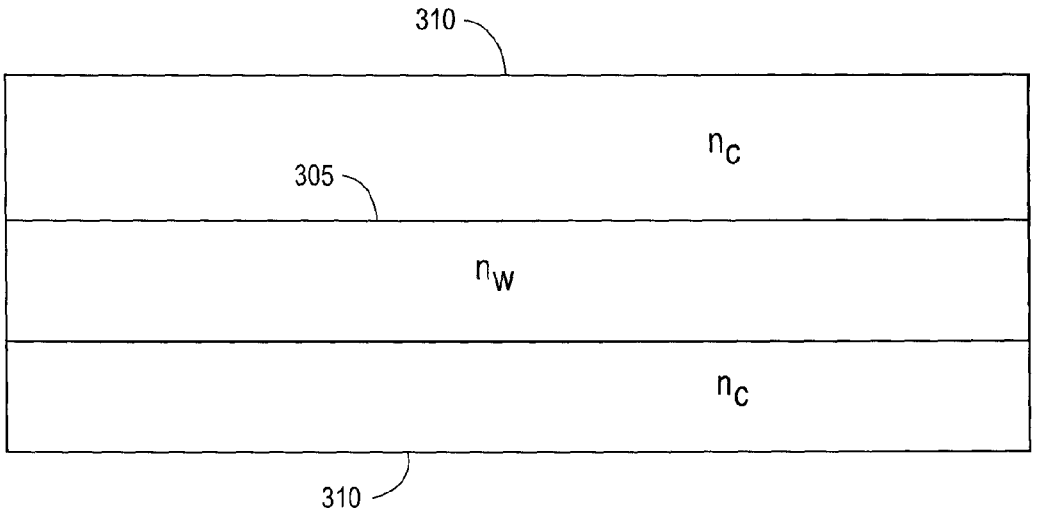


FIG. 4

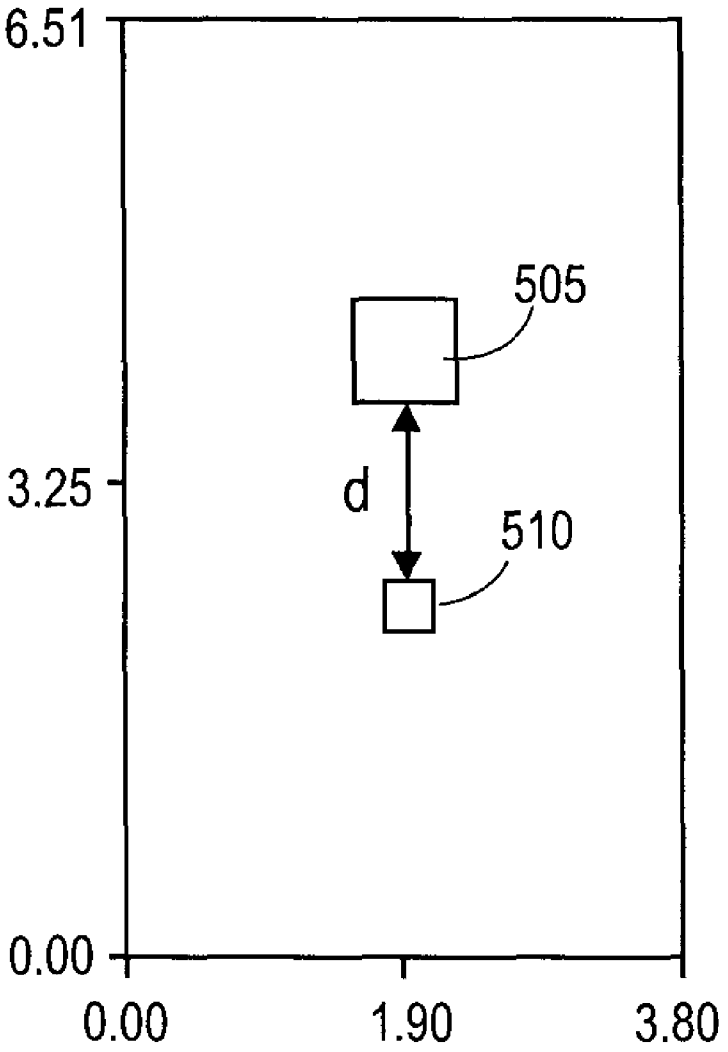


FIG. 5

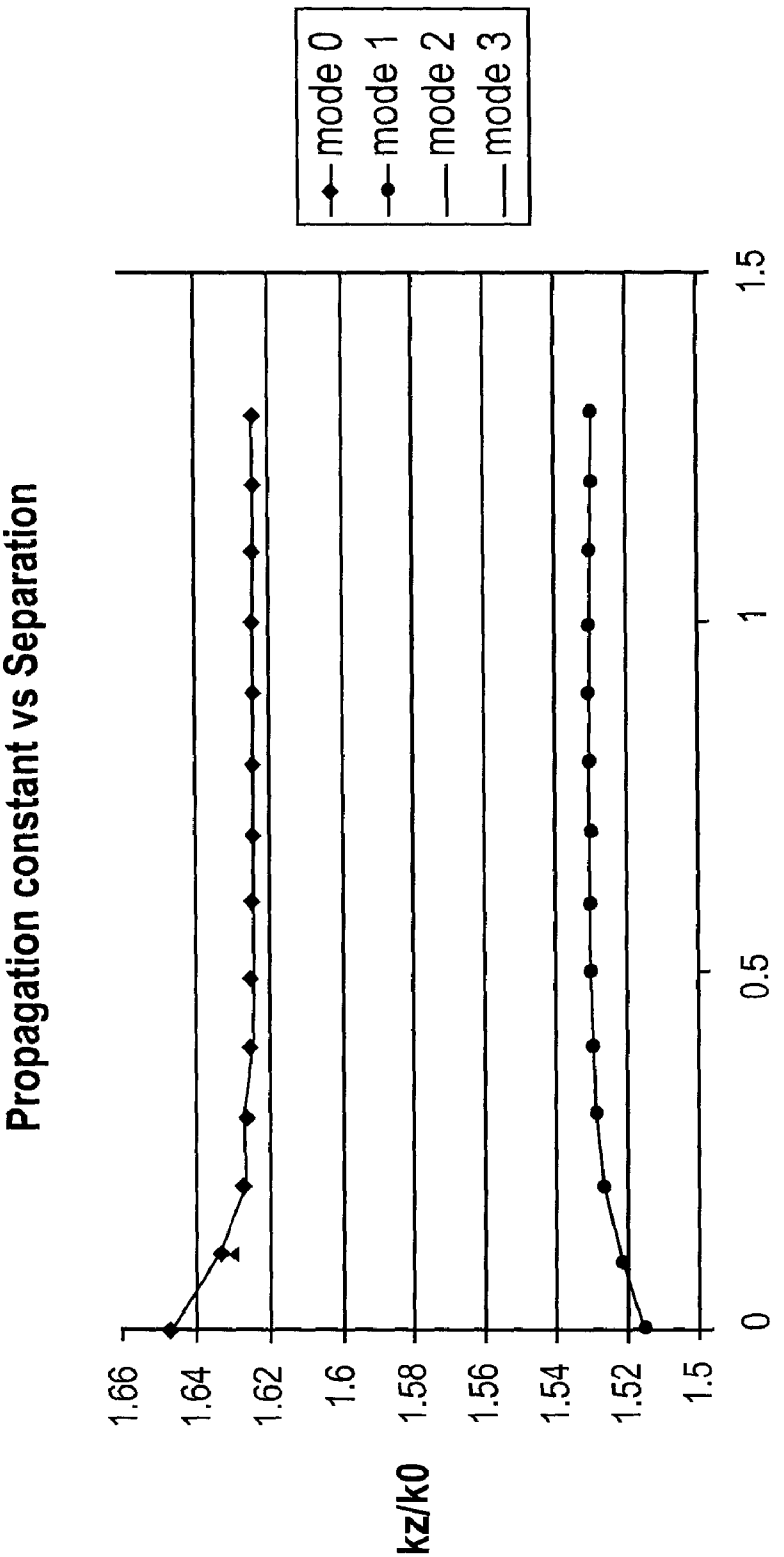

Propagation constant vs Separation
mode 0
mode 1
mode 2
mode 3
kz/k0
1.66
1.64
1.62
1.6
1.58
1.56
1.54
1.52
1.5
0
0.5
1
1.5
d (microns)

FIG. 6

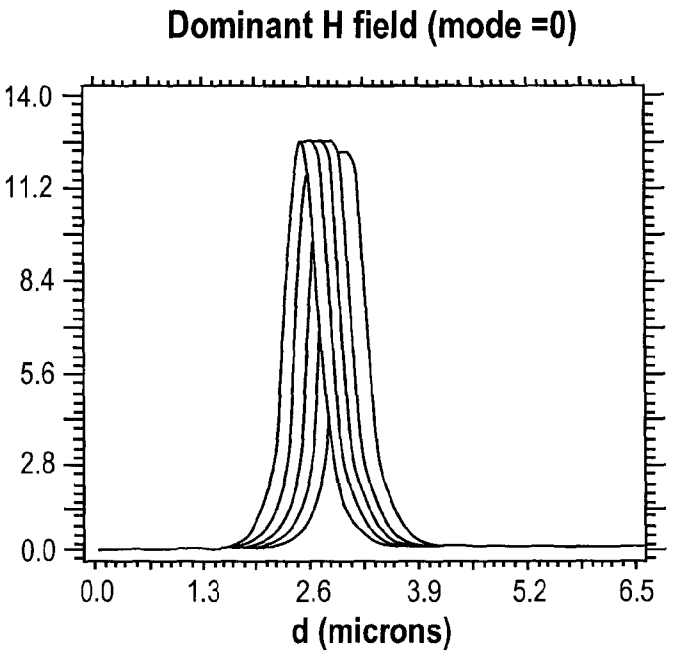

Dominant H field (mode =0)
14.0
11.2
8.4
5.6
2.8
0.0
0.0
1.3
2.6
3.9
5.2
6.5
d (microns)

FIG. 7A

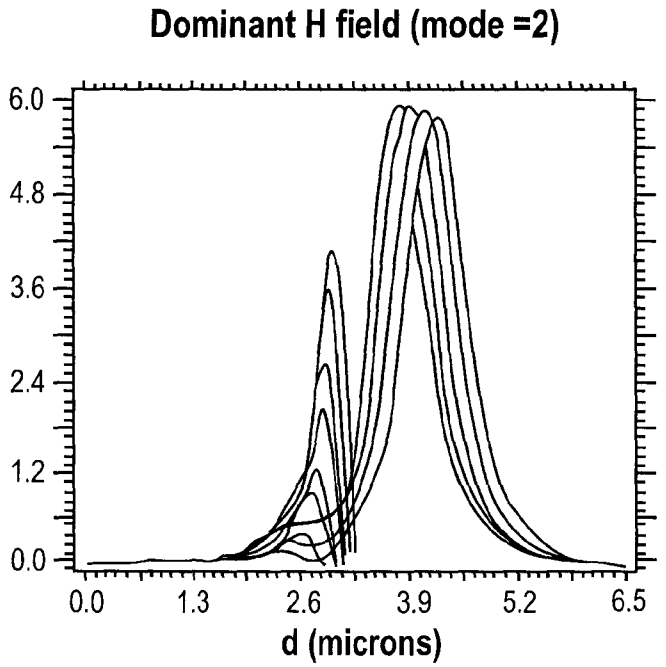

Dominant H field (mode =2)
6.0
4.8
3.6
2.4
1.2
0.0
0.0
1.3
2.6
3.9
5.2
6.5
d (microns)

FIG. 7B

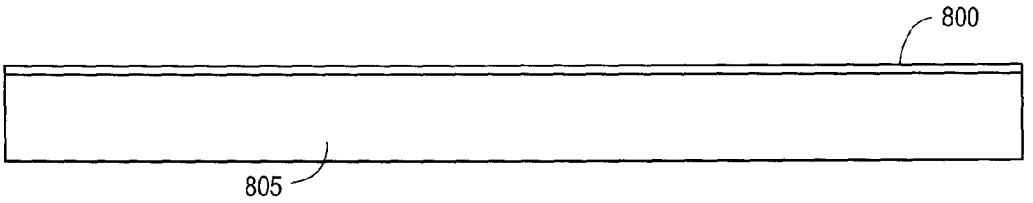


FIG. 8A

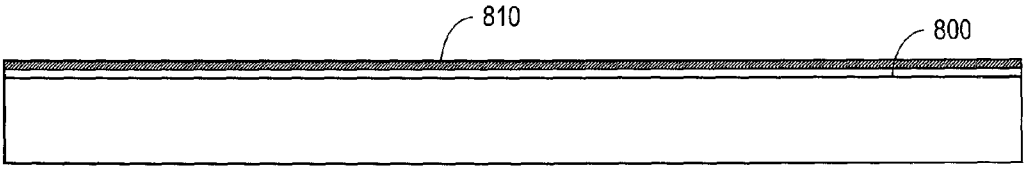


FIG. 8B

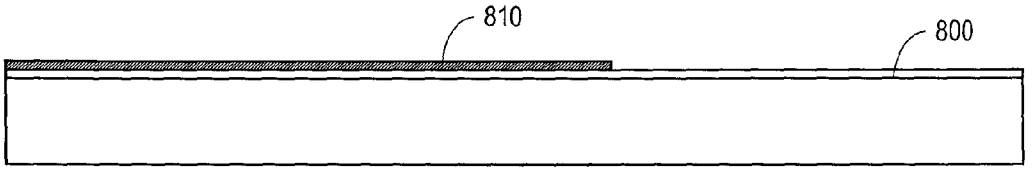


FIG. 8C

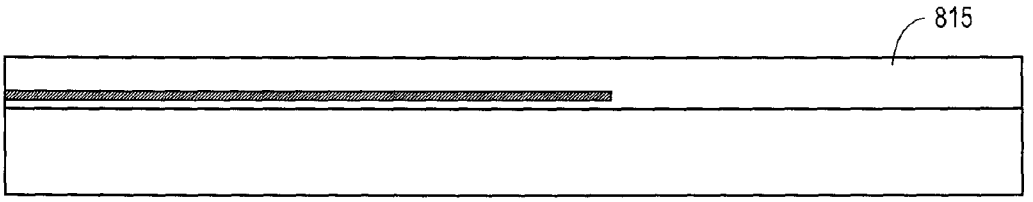


FIG. 8D

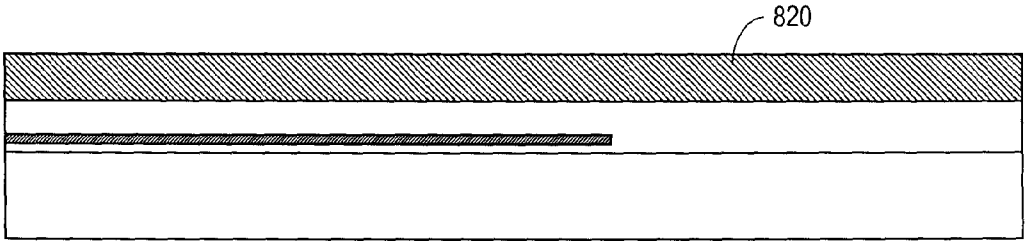


FIG. 8E

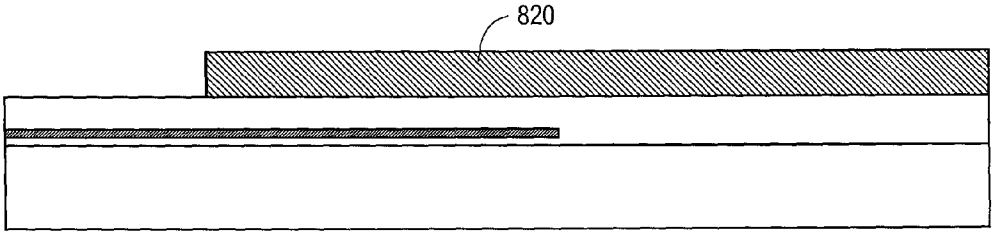


FIG. 8F

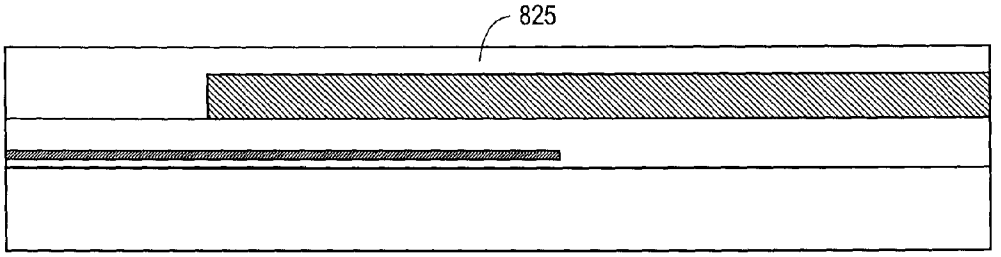


FIG. 8G

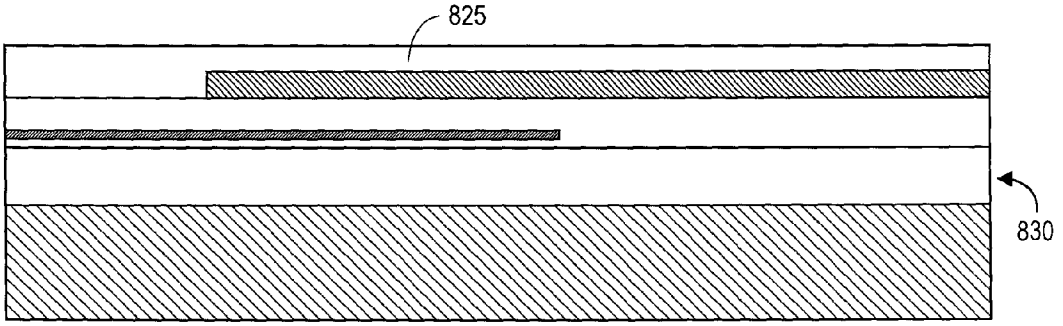


FIG. 8H

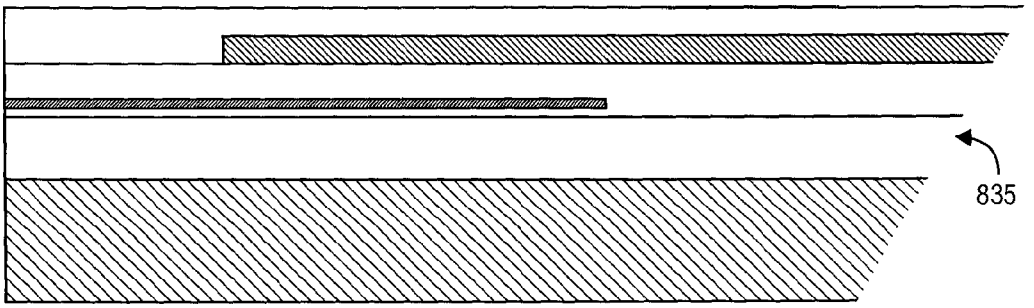


FIG. 8I

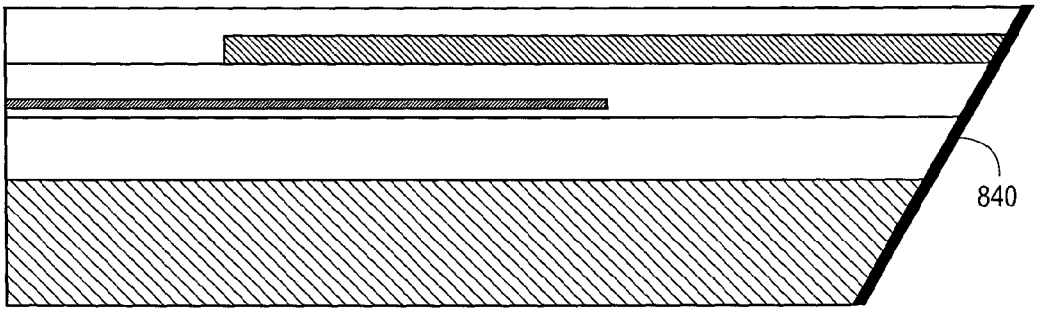


FIG. 8J

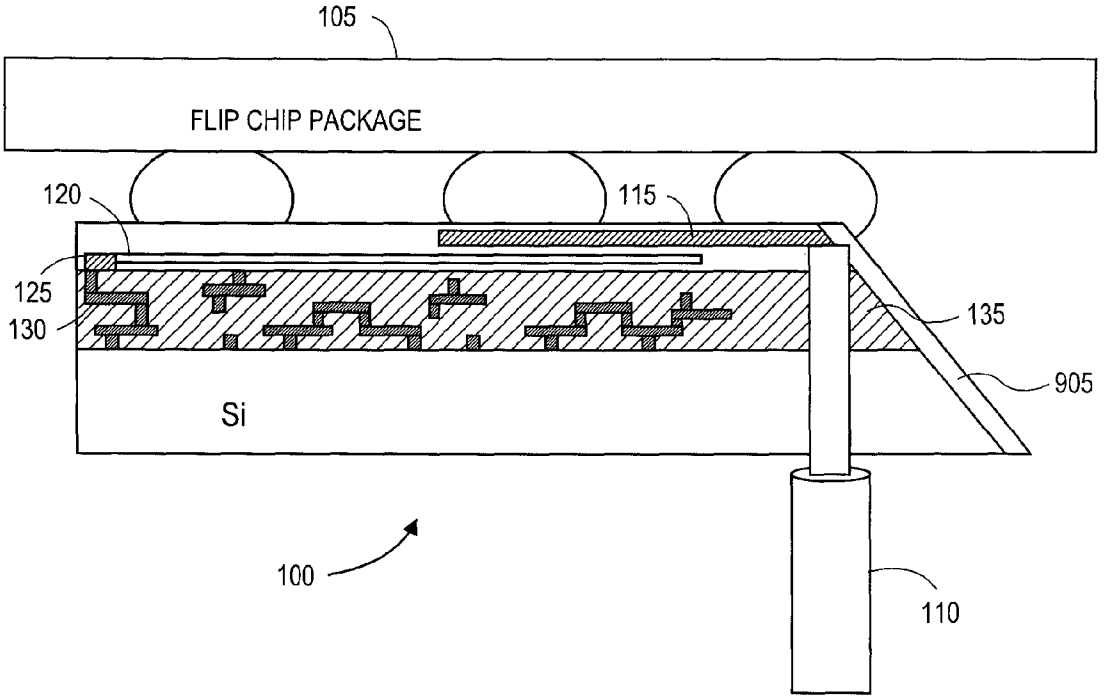


FIG. 9

EFFICIENT LIGHT COUPLER FROM OFF-CHIP TO ON-CHIP WAVEGUIDES

[0001] This is a Divisional Application of Ser. No. 12/031,665 filed Feb. 14, 2008, which is presently pending which is a continuation application of and claims priority to Ser. No. 10/421,640, filed Apr. 22, 2003 which is presently pending.

BACKGROUND

[0002] Opto-electronic integrated circuits (OEICs) may incorporate both electronic circuits and optical devices, such as integrated waveguides, modulators, switches, and detectors. The optical devices may be used for, e.g., optical clock distribution, intra-chip optical signaling, and chip-to-chip communication Both the electronic circuits and optical devices may be produced on silicon using complementary metal-oxide semiconductor (CMOS) fabrication techniques.

[0003] Light utilized by optical devices in an OEIC may be introduced into the chip by an external source, such as a vertical cavity surface emitting laser (VCSEL) or an optical fiber. The light from the external source may have a relatively large mode compared to that of the on-chip waveguides. The differences in mode size may present difficulties in efficiently coupling the relatively large mode off-chip light source to a small waveguide on the chip.

BRIEF DESCRIPTION OF THE DRAWINGS

[0004] FIG. **1** is a cross-sectional view of an opto-electronic chip bonded to a flip chip.

[0005] FIG. **2** is a plan view of an optical layer in the opto-electronic chip.

[0006] FIG. **3** is a sectional view of an integrated waveguide structure.

[0007] FIG. **4** is a plan view of an integrated waveguide structure.

[0008] FIG. **5** is a sectional view of adjacent low and high index contrast waveguides.

[0009] FIG. **6** is a chart showing the normalized propagation constant as a function of the separation of the waveguides of FIG. **5**.

[0010] FIGS. **7**A and **7**B are plots showing the localization of the dispersion curve in the waveguides of FIG. **5**.

[0011] FIGS. **8**A-**8**J show steps in an exemplary process for fabricating the opto-electronic chip shown in FIG. **1**.

[0012] FIG. **9** shows an opto-electronic chip according to an alternative embodiment.

DETAILED DESCRIPTION

[0013] FIG. **1** shows an opto-electronic integrated circuit (OEIC) (or "opto-electronic chip") **100** coupled to a flip chip package **105**. The flip chip package may include a light source **110**, e.g., a laser or optical fiber. Modulated light signals from the light source may be deflected into a low index contrast (LIC) waveguide **115** by a 45 degree mirror **118**. The LIC waveguide may be mode-matched to the light source **110** to minimize coupling loss. Light coupled into the LIC waveguide **110** may then be transferred from the LIC waveguide to a high index contrast (HIC) waveguide **120** by evanescent coupling.

[0014] The HIC waveguide **120** may be laid out in a pattern, e.g., a tree structure, to distribute the light across the chip, as shown in FIG. **2**. Photodetectors **125** may convert the light signals into electrical signals. The electrical signals may be transferred to electronic circuitry in the chip through electrical interconnects **130** in metallization layers **135** of the chip **100**.

[0015] The light source may be a single mode (SM) optical fiber, VCSEL (Vertical Cavity Surface Emitting Laser), or other single mode semiconductor laser. "Mode" refers to the solution of Maxwell's wave equation satisfying the boundary conditions of the waveguide, thus forming a unique pattern of standing wave in the radial direction on the cross section of the waveguide. A mode is characterized by its propagation constant (eigenvalue of the wave equation). A single mode light source may be appropriate for the relatively small waveguides present in the opto-electronic chip.

[0016] The light source may be positioned vertically with respect to the device side of the chip and placed in close proximity. The light may impinge on the surface of the chip and be transmitted through a transparent cladding film **150** (e.g., SiO_2) and across the LIC waveguide material **115**. Anti-reflective (AR) coatings may be provided on the chip surface to avoid reflection.

[0017] The light may then strike a 45 degree metal mirror and be reflected 90 degrees, in the same direction as the waveguide, i.e., parallel to the chip surface. The light may be trapped by total internal reflection and coupled into the LIC waveguide **115**. The index contrast of this waveguide (e.g., the difference between the indexes of refraction of the waveguide core and the surrounding cladding layer) may be tailored such that the mode size is close to that of the fiber to promote efficient coupling, thereby reducing the power requirement for the off-chip light source.

[0018] As shown in FIGS. **1** and **2**, the LIC waveguide **115** may be larger than the HIC waveguide **120**. The mode of the LIC waveguide **115** may more closely match the mode of the light source **110**. However, the bend radii of HIC waveguides may be much smaller (e.g., less than about 50 microns) compared to LIC waveguides, which may be only able to bend at about 1 mm radius. Having a smaller alloable bend radius allows for more efficient distribution of light about the chip. Accordingly, the LIC waveguide **115** may be used to couple light into the chip, and the HIC waveguide(s) **120** may be used for distribution and signaling.

[0019] A cross section and a top view of an integrated waveguide are shown in FIGS. **3** and **4**, respectively. The waveguide may be an optically guiding core **305** of a material with refractive index n_w surrounded by a cladding material with a different index of refraction, n_c. The high contrast of the refractive index between the two materials confines a lightwave to the waveguide **305**. The cladding material may be, e.g., silicon oxide (SiO_2) ($n_c \approx 1.5$). The waveguide material may be selected from, e.g., silicon nitride (Si_3N_4) ($n_w \approx 2$), silicon (Si) ($n_w \approx 3$), and silicon oxynitride (SiON) ($n_w \approx 1.55$). Silicon oxynitride may offer design flexibility because its refractive index may be varied by changing the content of nitrogen. The difference in the indexes of refraction between the core and the cladding determines the contrast, e.g., high index contrast or low index contrast.

[0020] Light may be transferred from the LIC waveguide **115** to the HIC waveguide **120** by evanescent coupling. Since the index of the HIC waveguide **120** is higher than that of the LIC waveguide **115**, the light gets coupled through the evanescent tail of the low index contrast mode. A lithographically patterned taper **200** may be used at the end of the LIC waveguide to make the transfer occur over a shorter length, as

shown in FIG. **2**. The interaction length may be designed such that substantially all of the light is transferred to the lower HIC waveguide **120**.

[0021] FIG. **5** shows two single mode waveguides **505**, **510** with n_{w1}=1.6 (LIC) and n_{w2}=2.0 (HIC), respectively, and cladding index n_c=1.5. The distance "d" may be varied from 0.0 to 1.2 microns. FIGS. **6** and **7**A-B illustrate modeling simulations for this waveguide configuration. FIG. **6** is a chart illustrating the normalized propagation constant as a function of the separation of waveguides. Each waveguide contains a doubly degenerate effective index when isolated. The upper branch of dispersion may be asymmetric mode localized to the HIC waveguide **510** (modes **0** and **1**) and the lower branch corresponds to LIC waveguide (modes **2** and **3**). FIG. **7**A shows that the upper branch of the dispersion curve is localized in the HIC waveguide and is weakly coupled to the LIC waveguide. FIG. **7**B shows that the lower branch of the dispersion curve is localized in LIC waveguide and strongly coupled to HIC waveguide. The coupling efficiency ranges from 70% at d=0.0 to 20% at d=0.5 based on the ratio of peak amplitudes in waveguides.

[0022] FIGS. **8**A-J show stages in the fabrication of the optical layers and 45 degree mirror in the chip according to an embodiment. A lower cladding film **800**, such as SiO_2 may be deposited on the top of the last metallization layer **805** in the chip, which may include electrical interconnect lines to electronic circuitry in the chip. A core material **810** for the HIC waveguide **120**, such as Si_3N_4, may be deposited on the lower cladding film **800**. The silicon nitride layer may then be etched to form a HIC waveguide pattern. An intermediate cladding layer **815**, e.g., silicon dioxide, may be deposited over the HIC waveguide layer **810**. Next, a core material **820** for the LIC waveguide **115** may be deposited on the intermediate cladding layer **815**. The silicon oxynitride layer may then be etched to form a LIC waveguide pattern. An upper cladding layer **825** may then be deposited on the LIC waveguide pattern.

[0023] The wafer may then be diced, producing an edge **830**. The edge **830** of the die may be polished to a 45 degree angle edge **835**. A thin layer **840** of a metal material such as Al may be applied, e.g., by sputtering or evaporation. Anti-reflective coatings may also be added to the top surface to reduce reflection. The light source, e.g., an optical fiber, may then be joined to the top of the upper cladding layer **825** of the LIC waveguide, e.g., melting the fiber to adhere to the surface or by use of an adhesive.

[0024] In another embodiment, light may enter the backside surface of the chip and hit a mirror **905** which is polished at 45 degrees, as in FIG. **9**. This structure may be used with light having a wavelength greater than about 1.2 microns.

[0025] A number of embodiments have been described. Nevertheless, it will be understood that various modifications may be made without departing from the spirit and scope of the invention. Accordingly, other embodiments are within the scope of the following claims.

1. A method comprising:
fabricating an integrated optical waveguide on a substrate;
polishing an edge of the integrated optical waveguide at an angle; and
coating the polished edge of the integrated optical waveguide with a reflective material to form a mirror positioned to couple light unto the integrated optical waveguide.

2. The method of claim **1**, wherein polishing the edge of the integrated optical waveguide comprises polishing an edge of a semiconductor die.

3. The method of claim **1**, wherein fabricating the integrated optical waveguide comprises fabricating the integrated optical waveguide substantially parallel to a surface of the substrate.

4. The method of claim **1**, further comprising coupling the substrate to a flip chip package so that light of a light source is deflected into the integrated optical waveguide.

5. The method of claim **10**, wherein:
fabricating the integrated optical waveguide comprises fabricating a low index contrast waveguide; and
the method further comprises fabricating a high index contrast waveguide adjacent to the low index contrast waveguide, wherein the high index contrast waveguide is separated from the low index contrast waveguide by a distance that allows light to evanescently couple from the low index contrast waveguide into the high index contrast waveguide.

6. The method of claim **5**, further comprising patterning the high index contrast waveguide into a distribution pattern.

* * * * *