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Title: LOW LOSS DIRECTIONAL COUPLING BETWEEN HIGHLY DISSIMILAR OPTICAL WAVEGUIDES FOR HIGH REFRACTIVE INDEX INTEGRATED PHOTONIC CIRCUITS

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LOW LOSS DIRECTIONAL COUPLING BETWEEN HIGHLY DISSIMILAR OPTICAL WAVEGUIDES FOR HIGH REFRACTIVE INDEX INTEGRATED PHOTONIC CIRCUITS

5 Reference to Related Applications

The present application claims priority from U.S. Provisional Patent Application Serial No. 61/428,216 filed 29-Dec-2010, the entirety of which is incorporated herein by reference.

10 Technical Field

The present invention relates to a method of achieving high efficiency optical signal coupling between low refractive index waveguides and high refractive index waveguides.

15 Background

In the field of microelectronics there is a push to integrate photonics and microelectronics in order to improve the performance of current electronic systems. The possibility of permitting optical communication between integrated chips via an optical bus would have a major impact on the performance of electronic systems. Research in this field is very active, however proposed solutions until now have been unsuitable and are difficult to realize in practice.

Efficient coupling of highly dissimilar refractive index waveguides has always been a problem in many applications.

For example, optical fiber waveguides have been employed to convey optical signals. Optical fibers include an optical fiber core within a cladding. Optical fiber waveguide to optical fiber waveguide butt-coupling requires high precision alignment. Semiconductor waveguides typically have smaller geometries and higher refractive indices compared to
optical fiber geometries and refractive indices. The geometry mismatch stems from mode confinement requirements, the higher refractive index of semiconductor waveguides demands smaller geometries. Butt-coupling between optical fibers and semiconductor waveguides require extremely high precision alignment and suffers from high coupling losses due to refractive index mismatches.

In the field of integrated opto-electronic devices, light (optical signal) coupling between "on chip" waveguides and external waveguides is conventionally done using butt-coupling between an external fiber core and the core of an on-chip waveguide or its optical interconnect device. On-chip opto-electronic devices include vertical cavity lasers, horizontal cavity lasers, photodiodes and phototransistors. On-chip optical devices include splitters and couplers.

What prevents major progress in the field is an intrinsic property of silicon, the principal semiconductor utilized in microelectronics, which has a high index of refraction (about 3.5) compared to that of optical fibers (about 1.47). The index of refraction of germanium, another important semiconductor utilized in microelectronics is about 4. This prevents efficient injection of an optical signal from one material to the other in two different ways. First, the large index of refraction difference between them causes the creation of reflections at the injection interface. Second, the required geometries of an optical fiber and of a waveguide of a high index of refraction for single mode optical signal propagation are radically different. Both of these factors reduce the ability to couple (transfer) optical signals with acceptable losses.

A similar problem exists in the field of biosensors between different materials than those employed in microelectronics however with comparable differences in refractive indices. While employing such hybrid integration technologies, an external optical signal may not be injected into a chip. However, the coupling experiences the same difficulty in injecting the signal into a layer of a high index of refraction.

On-chip waveguides typically comprise waveguides made of silicon or germanium having indices of refraction of about 3 to 4, which are much higher than the index of refraction for an optical fiber core (dielectric waveguide). For single mode fibers, core-
to-core butt-coupling requires high precision alignment and superior mechanical stability, both of which add significant cost to providing such optical connections. Not only must alignment be provided, but also a good match in the waveguide properties is required to ensure that the desired modes are coupled between waveguides. In many applications, optical coupling is such a challenge that designs resort to opto-electronic conversion of signals to use electrical coupling between on-chip and off-chip optical signals.

In coupling optical signals to and from on-chip waveguides or opto-electronic devices, conventional techniques involve mounting optical fibers with precision to rest horizontally on the integrated circuit with a prism reflector being used to redirect the light vertically into a waveguide or optical device on the integrated circuit. Conventional techniques also include precision mounting of the fiber vertically on the integrated circuit. These techniques are costly to implement due to difficulties in reproducing and maintaining alignment precision.

Recently evanescent field waveguide coupling has been proposed for optical signal coupling between an optical fiber waveguide and a semiconductor waveguide.

A theoretical treatise was provided by Borges, B.-H. V. and Herczfeld, P. R., entitled “Coupling from a Single Mode Fiber to a III-V Thin-Film Waveguide via Monolithic Integration of a Polymeric Optical Waveguide”, Journal of the Franklin Institute, vol. 335B, no 1, p. 89-96, 1998. Borges describes the results of theoretical modeling of evanescent field waveguide coupling between a polymer waveguide and a sheet waveguide of unlimited extent as well results of modeling evanescent field waveguide coupling between a polymer waveguide and a sheet waveguide of unlimited extent having a step discontinuity. While the mathematical modeling seems to suggest promising coupling efficiencies, the presented results cannot be employed in practice as usable waveguides have limited widths and therefore the presented results cannot be reproduced in practical implementations. Experimental trials attempting to duplicate Borges account only for a small fraction of the promised results. An effective refractive index variation is described by Borges, at the bottom of page 90 thereof, to come from exploiting “linear and quadratic electro-optic effects, as well as plasma, band filling, and
band shrinkage to yield a high figure of merit for index modulation”. Such coupling makes use of an important perturbation of the optical field at the entrance of the chip. The semiconductor upper cladding creates the perturbation and the optical field first partially couples into the upper cladding to finally transfer to the waveguide layer. That approach also creates a significant amount of radiative (lossy) mode coupling and higher order mode coupling which have not been addressed by Borges. Also, a number of assumptions have been demonstrated to be wrong in respect of structures having high refractive index differences. Furthermore, the lack of symmetry in the Borges approach prevents reverse optical signal (light) propagation from inside of the chip to the outside.

Further attempts at implementing evanescent field waveguide coupling describe tapered structures that slowly adapt the optical field of a first waveguide to match the optical field of a second waveguide. Such structures are difficult to fabricate due to a requirement for three-dimensional (3D) shaping during manufacture.

For example, one attempt at addressing the coupling problem provided tapered waveguides having large geometries in high refractive index materials. Numerous proponents have simulated such devices, and the simulations seem to suggest high optical signal injection efficiencies. Such attempts include: Dai, D., He, S. and Tsang, H.-K. "Bilevel Mode Converter Between a Silicon Nanowire Waveguide and a Larger Waveguide”, Journal of Lightwave Technology, vol. 24, no 6, p. 2428-33, June 2006; and Doylend, J. K. and Knights, A. P. "Design and Simulation of an Integrated Fiber-to-Chip Coupler for Silicon-on-Insulator Waveguides”, IEEE Journal of Selected Topics in Quantum Electronics, vol. 12, no 6, p. 1363-70, November 2006. While these simulations might suggest polarization independent solutions, only a limited number of such devices have been manufactured given the 3D nature of the devices.

Another attempt included employing a large size waveguide coupled with a reverse tapered waveguide of high refractive index described by Galan, J., Sanchis, P., Sanchez, G. and Marti, J., "Polarization Insensitive Low-Loss Coupling Technique between SOI Waveguides and High Mode Field Diameter Single-Mode Fibers”, Optics Express, vol. 15, no 11, p. 7058-65, 2007. According to this attempt, such geometry
permits obtaining good injection efficiency and has little polarization sensitivity. However, problems arise from the requirement for manufacturing a suspended structure which is very fragile. Furthermore, the tapered waveguide has to have extremely small dimensions. Such implementations demand use of high resolution lithography at increased costs.


Yet another attempt includes employing a diffractive grating engraved directly into the high refractive index material as described by: Roelkens, G., Van Campenhout, J., Brouchkaert, J., Van Thourhout, D., Baets, R., Romeo, P. R., Regreny, P., Kazmierczak, A., Seassal, C., Letartre, X., Hollinger, G., Fedeli, J. M., Di Cioccio, L. and Lagae-Blanchard, C., in “III-V/Si Photonics by Die-to-Wafer Bonding”, Materials Today, vol. 10, no 7-8, p. 36-43, July-August 2007; Taillaert, D., Van Laere, F., Ayre, M., Bogaerts, W., Van Thourhout, D., Bienstman, P. and Baets, R., in “Grating Couplers for Coupling Between Optical Fibers and Nanophotonic Waveguides”, Japanese Journal of Applied Physics, vol. 45, no 8A, p. 6071-6077, 2006; and Taillaert, D. and Baets, R., in US patent 7,065,272 B2 entitled “Fiber-to-waveguide coupler” published April 26, 2005. Initial experimental results appear to show that the signal injection efficiency is relatively good and polarization independent. Also, the injection is totally independent of the “state” of the facets. Despite these advantages, the required fabrication complexity is high, because such implementations demand high resolution lithography and high precision engraving techniques. Furthermore, alignment has to be controlled very well in order to avoid optical signal losses.
Other attempts propose coupling schemes requiring nanofabrication, which can also be difficult to incorporate into CMOS chips.

There is a need in the field for increasing optical coupling efficiencies between low refractive index (dielectric) waveguides and high refractive index semiconductor waveguides.

**Summary**

It has been found that continuously varying the thickness and/or width of structures to provide prior art tapers for adiabatic energy transfer from a guiding structure to another requires extreme complexity. In contrast it has been discovered that employing layer thickness control during semiconductor fabrication provides beneficial manufacturing advantages.

It has been discovered that the above identified prior art shortcomings can be addressed via a two step approach wherein:

1. Coupling an optical signal propagating in an external optical fiber into an intermediary waveguide having a refractive index comparable to that of the external optical fiber, the intermediary waveguide being waferscale manufactured employing standard micrometer resolution photolithographic techniques providing a relatively simple and effective coupler.

2. Coupling the optical signal propagating in the intermediary waveguide into a nanometric high refractive index semiconductor waveguide. The proposed solution implements directional optical coupling. The coupling is preferably done from the fundamental mode of a first waveguide to the fundamental mode of a second waveguide (single mode light propagation). The first waveguide can be the lower refractive index waveguide or the higher refractive index waveguide, depending on the application. The coupling scheme described is reciprocal with respect to the waveguides, which means that an optical signal can travel efficiently in both wave propagation directions, from the intermediary waveguide to the semiconductor
waveguide or from the semiconductor waveguide to the intermediary waveguide. Directional coupling arises when an output waveguide is located in the proximity of an input waveguide in which an optical signal propagates. If the evanescent field extending from the propagating mode of the input waveguide conveying the optical signal enters the core of the neighboring waveguide, such coupling usually happens through tunneling-like phenomena. When the two waveguides are similar in terms of wave vector amplitude and direction, an efficient energy transfer can take place.

Embodiments according to the proposed solution require only little in terms of fabrication complexity. Waveguide alignment is provided by photolithography of semiconductor structures having a high refractive index. Such alignment is relatively simple to produce and is enabled by a precise control of layer thicknesses for the interface between the nanometric high refractive index waveguide and the intermediary low refractive index waveguide. Such optical signal coupling into a waveguide having a nanometric thickness can be realized efficiently.

It has also been discovered that the dimensions of the waveguides can be easily tuned in many cases to allow efficient (optical signal) light coupling between very dissimilar waveguides.

It has further been discovered that the proposed solution is compatible with standard CMOS fabrication processes and therefore has wide applicability. The proposed solution permits coupling of external optical signals (e.g. from an optical fiber) (e.g. a hybrid optical source) into a photonic circuit inside a microchip, photonic circuit which is fabricated from high refractive index materials. The reverse is equally possible.

In accordance with an aspect of the invention there is provided an integrated circuit physical optical Input/Output (I/O) interface for coupling at least one mode of an optical signal between a waveguide external to the integrated circuit and a high refractive index waveguide internal to the integrated circuit, the physical optical interface comprising: an I/O waveguide conveying an external optical signal near the integrated circuit along an external signal path, said I/O waveguide having a first refractive index; and a high
refractive index coupler waveguide forming part of the integrated circuit and conveying an internal optical signal along an internal signal path, said high refractive index waveguide having a second bulk refractive index substantially dissimilar from said first refractive index, said high refractive index waveguide having at least a portion with a thickness configured to exhibit an effective refractive index substantially matching said first refractive index of said I/O waveguide, said high refractive index waveguide and said I/O waveguide being arranged substantially parallel and in proximity with an overlap therebetween to permit tunnel coupling of said at least one mode of said optical signal between said internal signal path and said external signal path.

In accordance with another aspect of the invention there is provided an optical interconnect comprising at least one integrated circuit physical optical Input/Output (I/O) interface for coupling at least one mode of an optical signal between a waveguide external to the integrated circuit and a waveguide internal to the integrated circuit, the physical optical interface comprising: an I/O waveguide conveying an external optical signal near the integrated circuit along an external signal path, said I/O waveguide having a first refractive index; and a coupler waveguide forming part of the integrated circuit and conveying an internal optical signal along an internal signal path, said internal waveguide having a second bulk refractive index substantially dissimilar from said first refractive index, said semiconductor waveguide having at least a portion with a thickness configured to exhibit an effective refractive index substantially matching said first refractive index of said I/O waveguide, said internal waveguide and said I/O waveguide being arranged substantially parallel and in proximity with an overlap therebetween to permit tunnel coupling of said at least one mode of said optical signal between said internal signal path and said external signal path.

In accordance with a further aspect of the invention there is provided a process for manufacturing a low loss coupler, the process comprising patterning an oxidation mask on top of a device layer, and thinning the device layer down to a thickness comprised between 20nm and 200nm.

In accordance with a further aspect of the invention there is provided a process for manufacturing a low loss coupler, the process comprising fabricating a shadow mask on
top of a high refractive index layer; and plasma etching resulting in vertically tapered structures.

In accordance with a further aspect of the invention there is provided a process for manufacturing a low loss coupler, the process comprising: fabricating a shadowing mask on top of a high refractive index layer, said shadowing mask having an overhang; depositing an etching mask material over said overhanging shadowing mask, said etching mask material forming a taper region under the overhang; removing said overhanging shadowing mask; and plasma etching both said high refractive index layer and etching mask vertically, said taper region causing said high refractive index layer to be etched non-uniformly forming a tapered structure therein as said tapered etching mask retreats across said tapered region.

In accordance with a further aspect of the invention there is provided a process for manufacturing a low loss coupler, the process comprising employing a shadowing mask during deposition.

In accordance with yet another aspect of the invention there is provided a optical signal coupler for coupling at least one mode of an optical signal between at least one Input/Output (I/O) waveguide conveying an external optical signal along an external signal path and a corresponding high refractive index waveguide forming part of an integrated circuit, each said high refractive index waveguide conveying an internal optical signal along an internal signal path, said coupler comprising: each of said at least one I/O waveguide having a first bulk refractive index, each said corresponding high refractive index waveguide having a second bulk refractive index substantially dissimilar from said first refractive index; at least one alignment structure for positioning said at least one I/O waveguide with respect to said corresponding high refractive index waveguide substantially in parallel, in proximity and with an overlap therebetwen to permit tunnel coupling of said at least one mode of said optical signal between said external signal path and said internal signal path, said high refractive index waveguide having at least a portion with a thickness configured to exhibit an effective refractive index substantially matching said first refractive index of said I/O waveguide.
Brief Description of the Drawings

The invention will be better understood by way of the following detailed description of embodiments of the invention with reference to the appended drawings, in which:

Figure 1 is a schematic side view diagram illustrating aspects of the proposed solution;

Figure 2a is a plot illustrating, in accordance with the proposed solution, a variation of an effective refractive index of a high refractive index waveguide with waveguide layer thickness for a given waveguide width, wherein the width is assumed to be very large compared to the thickness;

Figure 2b is a plot illustrating, in accordance with the proposed solution, variations of the effective refractive index of a silicon waveguide for both polarization states, for a waveguide width of 4.2 microns and a free space wavelength of 1.55μm;

Figure 2c is a plot illustrating, in accordance with the proposed solution, a variation of a coupling efficiency from a low refractive index material waveguide having a core index of 1.57 to a silicon waveguide as a function of effective refractive index detuning, wherein a detuning value of 0 corresponds to a perfectly matched structure;

Figure 2d is a plot illustrating, in accordance with the proposed solution, a variation of the coupling efficiency from a low refractive index material waveguide having a core index of 1.57 to a silicon waveguide as a function of the width of the silicon waveguide;

Figure 2e is a plot illustrating, in accordance with the proposed solution, a variation of the coupling efficiency from a low refractive index material waveguide having a core index of 1.57 to a silicon waveguide as a function of misalignment between the centers of the waveguides;

Figure 3a is a schematic diagram illustrating, in accordance with the proposed solution, a side view of an embodiment of the proposed solution wherein the first waveguide is an optical fiber from which some cladding has been removed in order to allow bringing the
core close enough to the high refractive index waveguide, the exposed optical core representing an intermediary waveguide;

Figure 3b is another schematic diagram illustrating a top view of the embodiment illustrated in Figure 3a;

5 Figure 3c is yet another schematic diagram illustrating a cross-sectional view perpendicular to a circular optical fiber core axis;

Figure 4a is a schematic diagram illustrating a side view of another embodiment of the proposed solution wherein the first waveguide is an intermediary waveguide to which light is butt-coupled from an optical fiber of a similar refractive index;

10 Figure 4b is another schematic diagram illustrating a top view of the embodiment illustrated in Figure 4a;

Figure 4c is a further schematic diagram illustrating a cross-sectional view perpendicular to the optical fiber core axis with a circular optical fiber shown in dotted lines to improve clarity. A v-groove structure is employed to provide improved (optimal) alignment;

Figure 4d is yet another schematic diagram illustrating a front view of the embodiment, showing the optical fiber in a V-groove alignment structure;

Figure 5a is a schematic diagram illustrating, in accordance with a further embodiment of the proposed solution, a top view of packaging aspects of bringing an optical bus into a package for connection to a semiconductor chip;

Figure 5b is another schematic diagram illustrating a cross-sectional view of the embodiment illustrated in Figure 5a along the optical bus/waveguides;

Figure 5c is yet another schematic diagram illustrating another cross-sectional view of the embodiment illustrated in Figure 5a perpendicular to the waveguides;

25 Figure 6a is a schematic diagram illustrating, in accordance with a further embodiment of the proposed solution, a side view of an implementation wherein the high refractive
index material waveguide is fabricated on top of the (intermediary) low refractive index waveguide layer;

Figure 6b is another schematic diagram illustrating a top view of the embodiment of Figure 6a;

Figure 6c is yet another schematic diagram illustrating a cross-sectional view of the embodiment of Figure 6a;

Figure 7a is schematic diagram illustrating, in accordance with a further embodiment of the proposed solution, a top view of a structure controlling coupling length by patterning the intermediary waveguide with an s-bend;

Figure 7b is schematic diagram illustrating, in accordance with a further embodiment of the proposed solution, a top view of a structure controlling coupling length by patterning the high refractive index waveguide with an s-bend;

Figure 8a is a schematic diagram illustrating, in accordance with a further embodiment of the proposed solution, a top view of a single input being distributed over many outputs, wherein a intermediary waveguide is patterned with s-bends to control each coupling length;

Figure 8b is another schematic diagram illustrating, in accordance with a further embodiment of the proposed solution, a top view of a single input being distributed over many outputs, wherein high refractive index waveguides are patterned with s-bends to control each coupling length;

Figure 8c is yet another schematic diagram illustrating, in accordance with a further embodiment of the proposed solution, a top view of a single input being distributed over many outputs, wherein a demultiplexing structure is employed to distribute an optical signal over many outputs;

Figure 9a is a schematic diagram illustrating, in accordance with a further embodiment of the proposed solution, a top view of multiple inputs being mixed together into a single
output, wherein a high refractive index waveguide is patterned to form multiple directional coupler sections;

Figure 9b is another schematic diagram illustrating, in accordance with a further embodiment of the proposed solution, a top view of multiple inputs being mixed together into a single output, wherein multiple intermediary waveguides are patterned to form multiple directional coupler sections;

Figure 9c is yet another schematic diagram illustrating, in accordance with a further embodiment of the proposed solution, a top view of multiple inputs being mixed together into a single output, wherein the high refractive index waveguide includes a multiplexing structure to mix multiple input optical signals into a single output;

Figure 10a is a schematic diagram illustrating, in accordance with a further embodiment of the proposed solution, a top view of a directional coupler structure where an input optical signal is coupled from a single intermediary waveguide to two high refractive index waveguides simultaneously, the two high refractive index waveguides being located side by side addressing a polarization dependency of the proposed solution;

Figure 10b is a schematic diagram illustrating a cross-sectional view of the directional coupler structure of Figure 10a;

Figure 11a is a schematic diagram illustrating, in accordance with a further embodiment of the proposed solution, a top view of a directional coupler structure where an input optical signal is coupled from a single intermediary waveguide to two high refractive index waveguides simultaneously, the two high refractive index waveguides being located one above and one below of the intermediary waveguide addressing a polarization dependency of the proposed solution;

Figure 11b is a schematic diagram illustrating a cross-sectional view of the directional coupler structure of Figure 11a;

Figure 12 is a schematic diagram illustrating, in accordance with a further embodiment of the proposed solution, a side view of a structure where the high refractive index waveguide includes multiple sections of different thicknesses within the coupling region
to optimize both TE and TM directional coupling into a single high refractive index waveguide;

Figure 13a is a schematic diagram illustrating, in accordance with a further embodiment of the proposed solution, a side view of a coupler structure having at least four waveguide layers (including a transfer waveguide);

Figure 13b is a schematic diagram illustrating a top view of the coupler structure of Figure 13a;

Figure 14a is a schematic diagram illustrating, in accordance with a further embodiment of the proposed solution, a side view of a structure wherein the intermediary waveguide is curved in order to allow a butt-coupling from the top of the chip;

Figure 14b is a schematic diagram illustrating, in accordance with a further embodiment of the proposed solution, a side view of a structure where the intermediary waveguide includes a structure for redirecting the optical signal into the waveguide plane and allowing a butt-coupling from the top of the chip;

Figure 15a is a schematic diagram illustrating, in accordance with a further embodiment of the proposed solution, a side view of an optical signal transport structure between light sources built on a chip;

Figure 15b is a schematic diagram illustrating a top view of the optical signal transport structure of Figure 15a;

Figure 16a is a schematic diagram illustrating, in accordance with a further embodiment of the proposed solution, a side view of a flip-chip packaged device, wherein the low refractive index waveguide is built into the package and the high refractive index waveguide is built on top of the chip;

Figure 16b is a schematic diagram illustrating a top view of the flip-chip packaged device of Figure 16a;

Figure 16c is a schematic diagram illustrating a cross-sectional view of the flip-chip packaged device of Figure 16a;
Figure 17a is a schematic diagram illustrating a side view of a first process step of a LOCal Oxidation of Silicon (LOCOS) process for tuning the high refractive index waveguide layer thickness in accordance with the proposed solution, process step which includes depositing an oxidation mask;

Figure 17b is a schematic diagram illustrating a side view of a second process step of the LOCOS process for tuning the high refractive index waveguide layer thickness;

Figure 17c is a schematic diagram illustrating a side view of the outcome of a LOCOS processed region, wherein the thinner part of the silicon layer forming the high refractive index waveguide is tuned for optimal optical power transfer from or to a dielectric (transient) waveguide;

Figure 18a is a schematic diagram illustrating a side view of a shadow mask structure fabricated on top of a wafer in accordance with the proposed solution;

Figure 18b is a schematic diagram illustrating the effect of a shadowing mask during a chemical or physical deposition procedure (CVD, Sputtering, etc.);

Figure 18c is a schematic diagram illustrating the outcome after chemical or physical deposition has been performed in the presence of a shadow mask, providing a tapered region having a smooth transition;

Figure 18d is a schematic diagram illustrating the result of an etching process performed on the layered structure of Figure 18c;

Figure 18e is a schematic diagram illustrating the result of removing the etching mask from the layered structure of Figure 18d;

Figure 19a is a schematic diagram illustrating the top view of an embodiment wherein the effective index of the high refractive index waveguide is tuned by defining its width; and

Figure 19b is a schematic diagram illustrating a cross-sectional view of the device of Figure 19a,
wherein similar features bear similar labels throughout the drawings.

**Detailed Description**

The proposed solution includes a single thickness adjustment of a high refractive index layer enabling the fabrication of a waveguide having the intrinsic high refractive index to exhibit an effective refractive index that matches the effective refractive index of a low core index waveguide (effective refractive index between 1.4 and 1.6). The proposed solution benefits from an easily controlled thickness at nanometer scale via a number of deposition/growing processes. The fabrication of a robust optical directional coupler can be achieved by tuning the high refractive index material thickness.

As illustrated in Figure 1, a first waveguide 1 is placed nearby (adjacent) and parallel to a second waveguide 2. The first waveguide is made of a low refractive index material having a refractive index n1. The second waveguide is made of a high refractive index material having a bulk refractive index n2. The first waveguide is surrounded by cladding materials, or material combinations 3, and 4 (and 5), propagates a light signal of a given wavelength with a given polarization, and has an effective index neff1 of its fundamental mode. The second waveguide 2 is surrounded by cladding materials, or material combinations 4 and 5 (and 3), propagates a light signal of the same wavelength and same polarization, and has an effective index neff2 of its fundamental mode equal or close in value to neff1. The effective refractive indexes mentioned herein are always with respect to the fundamental modes. It is understood that the above layers and waveguides are wafer-level fabricated on a substrate (10).

In accordance with the proposed solution, the high refractive index material thickness 7 (t1) of the second waveguide 2 can be optimized to allow the effective index neff2 to be equal to or close to neff1. As illustrated on Figure 2b, the physical properties of the materials employed in fabricating the silicon second waveguide 2 are such that the effective refractive index of the silicon waveguide changes abruptly with silicon waveguide thickness 7. A similar abrupt change is experienced by waveguides
including germanium and to some extent in materials characterized as III-V semiconductors which can be useful for optoelectronics.

The overlapping region $6 \ (L_1)$ between the two waveguides 1 and 2 can be optimized to provide the best optical power transfer possible from one waveguide to the other. The extent of the overlap along the waveguides is known as coupling length (distance) $L_c$.

A waveguide separation distance $8 \ (d_1$ in Figure 1), for example implemented via a waveguide separation layer of cladding material 4, is small enough to allow directional optical coupling phenomena such as tunneling to take place. Directional coupling occurs via an extension of the evanescent field from the propagating mode of an input waveguide propagating light which enters the core of a neighboring output waveguide.

Figure 2a illustrates a plot of the effective refractive index $n_{eff2}$ as a function of the high refractive index material thickness 7 ($t_1$) for a given waveguide width, a given wavelength and a given polarization. The variation illustrates a high tuneability of the effective index $n_{eff2}$ by controlling the high refractive index material thickness 7 ($t_1$).

Figure 2b illustrates a plot of the effective refractive index $n_{eff2}$ in the case where silicon is the high refractive index material. Both polarization states TE and TM are illustrated on the plot. It has been discovered that this coupling arrangement exhibits a polarization dependence as the high refractive index waveguide thickness 7 ($t_1$) cannot be optimized for both polarization states at the same time. Several applications benefit from this effect.

Figure 2c illustrates a variation of coupling efficiency as a function of the effective refractive index detuning between the intermediary 1 and the high refractive index 2 waveguides. Directional coupling is most efficient when the effective refractive indices of the two waveguides are very close in value.

Figure 2d illustrates an example plot of the effective refractive index as a function of waveguide width for an optimized high refractive index thickness. It has been discovered that the effective index has much less sensitivity with respect to the width.
parameter. Therefore, fabrication constraints with respect to the lateral dimension of the waveguide can be relaxed.

Figure 2e illustrates an example plot of the coupling efficiency as a function of the waveguide misalignment illustrating that in the proposed configuration(s), this parameter is not highly critical.

Figures 3a, 3b and 3c illustrate another embodiment of the proposed solution in accordance with which the first waveguide 1 includes an optical fiber 9 having an at least partially exposed core 12. The optical fiber has some of its cladding 10 removed in a way that allows its core 12 to be placed close enough to the high refractive index waveguide 2, for example by removing a portion of the cladding to provide a facet. The invention is not limited to the circular cross-section cladding and core fiber illustrated in Figure 3c. Figures 3a and 3b equally illustrate optical fibers with rectangular cores, and optionally with rectangular cladding. It has been found that a mismatch between a circular geometry of an optical fiber core 1, 12 compared to the rectangular geometry of the first waveguide 1 of Figure 1 does not have a significant impact on the coupling efficiency and comparable waveguide separations can be employed when the geometries are dissimilar. With reference to figures 3a and 3c, the fiber core 12 comes near or in contact with the waveguide separation layer 4 and is the first waveguide 1. Figure 3b illustrates that a mechanical positioning structure could be fabricated at the same time as the chip to allow easy positioning of the optical fiber. A polymer 11 can be used for fixing the optical fiber in place. (Further packaging and alignment structure details are presented herein below with reference to Figures 4a, 4b, 4c, 5a, 5b, 5c, 14a, 14b, 16a, 16b and 16c)

Figures 4a, 4b and 4c illustrate another embodiment including an optical fiber 9 butt-coupled to an intermediary waveguide 1. For certainty, Figures 4a and 4b are not limited to circular optical fibers with circular cores and apply equally well to optical fibers having rectangular cross-section cores, and optionally rectangular cross-section cladding. Figure 4c illustrates a V-groove approach for the positioning of an optical fiber having a circular cross-section cladding with respect to the intermediary waveguide. The circular cross-section optical fiber geometry is illustrated in dashed line for clarity,
however the invention is not limited circular cross-section optical fibers. For a rectangular cross-section core and circular cross-section optical fiber, the core would be illustrated by a dashed rectangle 12 (not shown). The intermediary low refractive index waveguide 1 is built on top of the high (intrinsic/material) refractive index waveguide 2. The invention is not limited to the V-groove alignment structure 14, other alignment structures fabricated for example by lithography, etching and/or deposition can be used. The shape of the optical fiber can be employed for proper alignment. Figure 4d illustrates the use of a polymer 11 ensuring a tight and refractive index matched interface between the fiber and the chip. (Further packaging and alignment structure details are presented herein below with reference to Figures 3a, 3b, 3c, 5a, 5b, 5c, 14a, 14b, 16a, 16b and 16c)

In accordance with another implementation illustrated in Figures 5a, 5b and 5c, a bus of optical fibers dock on the chip, each optical fiber in the bus coupling to a corresponding semiconductor waveguide structure. Each fiber directs its carried optical signal to where on the integrated circuit the optoelectronic component is located. For example the optical fiber bus can form an array. The fiber bus and I/O waveguides can be provided in a package that connects on top of the integrated circuit package as a standard module. The integrated circuit can be fabricated with its tunneling coupling waveguides flush with the surface of the integrated circuit package and hermetically sealed. For example multiple tunneling coupling waveguides can be wafer level fabricated in an array corresponding to an arrayed optical fiber bus on a socket. (Further packaging and alignment structure details are presented herein below with reference to Figures 3a, 3b, 3c, 4a, 4b, 4c, 14a, 14b, 16a, 16b and 16c)

For certainty, while in the above presented embodiments the high refractive index waveguide 2 is disposed under the first intermediary waveguide 1, the invention is not limited to such orientation. Figures 6a, 6b and 6c respectively illustrate side, top and cross-sectional views of an embodiment where the high refractive index waveguide 2 is built on top of the intermediary low refractive index waveguide 1.

Figure 7a illustrates an embodiment in which the coupling length 6 is controlled by a lateral deviation of the intermediary waveguide 1 while Figure 7b illustrates another
embodiment in which the coupling length 6 is controlled by deviating the high refractive index waveguide 2. It is also to be noted that the coupling length 6 can be controlled by deviating both coupling waveguides. Controlling the coupling length 6 controls the length of a standing wave pattern within the corresponding wave guide, the length of the standing wave pattern determining the degree of light (optical signal) coupling. The angle of lateral deviation can vary within a range being only limited by bending losses of the waveguide(s).

Figures 8a to 8c illustrate implementations of an embodiment providing optical signal distribution from an input waveguide to a waveguide bundle having multiple on-chip waveguides. The coupling lengths 6, 6' and 6'' are controlled individually to transfer the desired amount (fraction) of the input optical power to each semiconductor waveguide 2 in the bundle. For example, if the input power of a single wavelength optical signal has to be split between two output waveguides 2, the first coupling would be limited to a 50% of the input power and the second subsequent coupling would couple 100% of the remaining power (which is 50% of the input power). If the input optical signal is a multi-wavelength optical signal, it is envisioned that each coupling length 6 can be separately configured to couple 100% of the signal power of a corresponding wavelength into a corresponding semiconductor waveguide 2 of the bundle. Figure 8c illustrates 100% coupling of an input optical signal into a semiconductor waveguide 2, and a signal or power dispatching structure 25, for example an MMI coupler, apportions the power to a number of semiconductor waveguides 26 in a bundle.

Figures 9a to 9c illustrate implementations of an embodiment providing combination of multiple optical signals from a bundle having many input waveguides to one on-chip waveguide. As above, coupling lengths 6, 6' and 6'' can be employed to couple particular fractions of input optical power signals, as well to couple different wavelengths in to a semiconductor waveguide 2. Figure 9c illustrates power or signal dispatching structure 27, for example an MMI coupler, which combines a bundle of multiple inputs 12, 28 into a single output coupled to an intermediary (first) waveguide 1.

The very high efficiency dependency on the polarization can be used as an advantage in the case where one aims at separating the two polarizations. While polarization
dependency of the proposed solution is advantageous in such applications, such polarization dependency is not necessarily a drawback. The following embodiments describe polarization mode recombination after coupling:

Figures 10a, 10b and 10c illustrate an embodiment providing simultaneous (double) coupling of both polarizations of an optical signal. Double coupling into a bundle of waveguides can be realized by placing the second waveguide 2 and a third waveguide 2' in proximity to the first waveguide 1. Also, since the optimal high refractive index material thickness has to be tuned differently for each polarization, the second waveguide 2 and said third waveguide 2' are of different thicknesses, as well the coupling lengths 6, 6' are optimized separately for the high refractive index material waveguides 2, 2'.

With the second waveguide 2 and the third waveguide 2' placed side to side in the bundle, recombination can be achieved by merging the second waveguide 2 and the third waveguide 2' at some (downstream) point, for example through a Y junction, to add the two polarizations together into a single waveguide. Difference in thicknesses (7) t1, t1' between the second 2 and the third 2' waveguides are illustrated in Figure 10b.

Figures 11a and 11b illustrate another embodiment providing simultaneous (double) coupling of both polarizations of an optical signal. The second 2 and third 2' waveguides in the bundle are placed under and above the first waveguide 1. Again, the thickness (7) and the coupling lengths 6, 6' of the second waveguide 2 are optimized differently than those of the third waveguide 2'.

Figure 12 illustrates an embodiment providing simultaneous (double) coupling of both polarizations of an optical signal and recombination into the same waveguide 2. The second waveguide 2 has two different sections defined by at least two different thicknesses t1, t1'. The first section has a thickness t1 and coupling length 6 optimized for the coupling of a first polarization state and the second section has a thickness t1' and coupling length 6' optimized for the coupling of the second polarization state.
While not shown, different materials can be employed for the fabrication of the second 2 and the third 2' waveguides in order to provide simultaneous coupling both polarization into respective semiconductor waveguides 2, 2'.

The invention is not limited to one layer SOI-CMOS chips, and applies equally to chips having multiple layer waveguide structures, for example biochips and telecommunications chips. Figure 13a is a schematic diagram illustrating, in accordance with a further embodiment of the proposed solution, a side view of a coupler structure having at least four waveguide layers. Also, the invention is not limited to coupling optical signals traveling from outside of the chip to inside the chip and vice-versa, the signal coupling techniques described herein can be adapted to transfer an optical signal from layer to layer of a multilayer waveguide chip as illustrated in Figure 13a. Intermediary waveguides transferring optical signal between layers are referred to as transfer waveguides.

Figure 13b is a schematic diagram illustrating a top view of the same coupler structure illustrating that only some of the waveguides (1) need to be compatible in terms of butt-coupling with optical fibers.

While the above description has made reference to butt-coupling on chip die side facets, the invention is not limited thereto: Figure 14a illustrates an upturned intermediary waveguide 1 enabling a butt-coupling with an optical fiber 12 on a top chip die surface. Alternatively, (not shown) the optical fiber 12 could itself be bent instead of the intermediate waveguide 1.

Similarly Figure 14b illustrates the use of an input waveguide block structure 18 configured to provide butt-coupling between the optical fiber 12 and the intermediary waveguide 1 enabling a butt-coupling of the optical fiber 12 on a top chip die surface. The input structure 18 redirects the optical signal into the waveguide 1 plane.

For packaging and socket type optical signal coupling purposes, curved waveguides and/or input/output waveguide block structures (18) can be employed for ensuring correct alignment. In some implementations a microscope can be employed to ensure correct alignment, with reference to Figures 2d, 2e, 10a and 10b some degree of
misalignment can be tolerated. (Further packaging details are presented herein below with reference to Figures 3a, 3b, 3c, 4a, 4b, 4c, 5a, 5b, 5c, 16a, 16b and 16c)

The invention is not limited to external generation of the optical signal. Figures 15a and 15b are schematic diagrams illustrating, in accordance with a further embodiment of the proposed solution, an optical signal transport structure between light sources 31 and/or photodetectors 31' mounted on the same chip.

Figures 16a, 16b and 16c are schematic diagrams illustrating, in accordance with a further embodiment of the proposed solution, side, top and cross-sectional views of a flip-chip packaged device. The first (effective low refractive index) waveguide 1 is built into the package and the high refractive index waveguide 2 is built on top of the chip in a flipped wafer structure. A filling polymer 34 is chosen to have good optical properties and a refractive index lower than that of the effective low refractive index of waveguide 1. For example filling polymer 34 can be applied in fluid form and cured. The routing of the optical waveguides takes into account positions of flip-chip bonding contact beads. For certainty in Figures 16a to 16c top and bottom relationships are interchangeable, the layered structure would operate identically if all layers were illustrated in reverse vertical order as illustrated with reference to Figures 5a to 5c. The only reason Figures 16a to 16c have the illustrated orientation is to simplify understanding of the application of the filling polymer 34 in a single step. When waveguide(s) 1 are provided in a socket providing attachment to a chip including waveguide 2, filling polymer 34 can be omitted assuming that refractive index requirements are present or replaced by another structure not requiring fluid form application having the requisite refractive index. Curing of a fluid filling polymer 34 may or may not be required. Filling polymer 34 can also include a gelatinous material having high viscosity (and/or variable viscosity).

While packaging details presented herein above with reference to Figures 3a, 3b, 3c, 4a, 4b, 4c, 5a, 5b, 5c, 14a, 14b, 16a, 16b and 16c have concentrated on vertical alignment, xy-alignment mentioned herein above with reference to Figure 5 can be provided for implementing packaging aspects and features for example to implement a socket for optical signal coupling to and from an integrated chip. With reference to an
inverted Figures 16a and 16c, the flip-chip layered structure including layers 5' and 1 separately fabricate for example as a socket, can be positioned with respect to the layered structure including layers 10, 5, 4 and 2 on a mounted chip by employing at least one alignment structures. In some implementations a microscope can be employed to ensure correct alignment, with reference to Figures 2d, 2e, 10a and 10b some degree of misalignment can be tolerated.

For vertical alignment, beads 35 and/or V-groves as illustrated in Figures 3b, 3c, 4b and 4c can be employed. Sockets having an array of optical fiber waveguides 1 corresponding to an array of on-chip waveguides 2, need not necessarily have circular cross-section cores and/or circular cross-section claddings. Furthermore, when V-groves are employed for vertical alignment of a waveguide 1 array, V-groves are not required for each optical fiber. A combination of V-groves and beads 35 can also be employed.

Alignment structures, for example employing beads 35 and/or V-groves (Figures 3b, 3c, 4b and 4c) can also be employed for xy-alignment or at least one waveguide 1. When an array of waveguides 1 of a socket are to be coupled to an array of waveguides 2 on a chip, the invention is not limited to a one-to-one correspondence between xy-alignment structures and waveguides in corresponding arrays. Properties of polymer 34 alluded to above can for example be provided by a gelatinous material of high viscosity (and/or variable viscosity) which may or may not require curing.

With optical signal coupled into the thinned (second) semiconductor high refractive index waveguide 2, the optical signal continues propagation along semiconductor waveguide 2 to interface with the rest of the chip. In accordance with one implementation, optical circuitry of the chip could consist only of semiconductor waveguides having a thickness substantially equal to the optimal thickness high refractive index waveguide 2 at the coupling device. In accordance with another implementation, a transition between thinned semiconductor waveguides 2 configured for coupling optical signals and regular thickness semiconductor waveguides is provided. The transition is configured to minimize optical signal losses, for example by
gradually (smoothly) varying the thickness. In certain applications abrupt transitions can also be employed (to generate desired effects).

Figure 17a is a schematic diagram illustrating a first step of a LOCal Oxidation of Silicon (LOCOS) process for wafer level fabrication of semiconductor waveguides 2 of controlled thickness. A cover material layer 39 deposited on top of a silicon layer 38, acts as an oxidation mask (barrier) to silicon layer 37 to be oxidized. Without limiting the invention, layer 39 includes silicon nitride however other oxidation mask materials can be employed. The thickness of the barrier layer 39 has to be large enough to block oxygen diffusion therethrough. Layer 38 for example consists of silicon dioxide and can be used to prevent delamination of the oxidation mask layer 39. The thickness of the oxide layer 38 can be a few tenths of a nanometer.

Figure 17b is a schematic diagram illustrating a second step of the LOCOS process. Layer 38 is known as a silicon dioxide growth layer when exposed to high temperature oxidation. The oxide growth from the silicon layer 37' is limited by oxygen diffusion and has a tendency to produce a smooth transition between masked and unmasked regions. Oxidation control in this step provides thickness selection (control) in the high refractive index waveguide. For example, the silicon high refractive index waveguide layer is thinned down to a thickness between 20nm and 200nm by use of a standard oxidation process or an etching process.

Figure 17c is a schematic diagram illustrating a third step of the LOCOS process, where the masking layer and the deposited silicon dioxide growth layer have been removed. The removal procedure, for example includes a selective hydrofluoric acid based etch. The resulting silicon layer thickness is optimized for optical coupling with the low refractive dielectric transient waveguide (intermediary waveguide) 1 in the unmasked regions.

For certainty, the invention is not limited to the silicon layer 37, for example germanium, III-V materials, etc. useful for optoelectronics can also be employed.

Figure 18a is a schematic diagram illustrating a first step of a shadow masking process. Support blocks 41 are built from a photoresist pattern or another suitable material. A
shadow mask 42 is also built from a photoresist or another suitable material, for example a bonded silicon wafer or deposited metal layers.

Figure 18b is a schematic diagram illustrating a second step of the shadow mask process. Either, the high refractive index waveguide material 37 or a suitable masking material 44, 44' could be deposited employing a chemical or physical deposition procedure (CVD, Sputtering, etc.). It is noted that the shadow mask could also be used to directly etch the high refractive index waveguide layer 37 to thin it down to an optimal thickness. Shadow masking has proven to be efficient in both deposition and etching. The spacing 40 between the shadow mask 42 and the wafer surface affects the transition profile leading to a tapered transition.

Figure 18c is a schematic diagram illustrating a third step of the shadow mask process, wherein the shadow mask is removed which leaves the deposited layer 44 having a smooth transition between the fully exposed region and the shadowed region. It is noted that a similar transition would have been left subsequent to etching in the second step.

Figure 18d is a schematic diagram illustrating a fourth step of the shadow mask process, where the tapered etch mask 44' profile is transferred to the high refractive index waveguide layer 37' removing both mask 44' and high refractive index waveguide material in substantially equal amounts, as the mask 44' retreats. Such removal can be provided via various means, including chemical (etching), physical (plasma etching, ablation), etc. The tapered region provided by the deposition in the presence of a separated shadow mask results in a high refractive index waveguide regions of different thickness, wherein the first region (2) is tuned for optimal optical power transfer from or to a (dielectric) waveguide 1. The remaining waveguide layer 37' has a smooth transition between the masked and unmasked regions.

Figure 18e is a schematic diagram illustrating a fifth step of the shadow mask process, wherein any masking material 44' is selectively removed, only the high refractive index waveguide layer 37' remains forming the semiconductor waveguide 2.
Figure 19a and 19b are schematic diagrams illustrating, in accordance with the proposed solution, top and cross-sectional views of yet another embodiment wherein the low refractive index (transient) waveguide 1 and the high refractive index waveguide 2 are built side by side on a wafer 10. A high performance etching process is employed to achieve the illustrated aspect ratios in the high refractive index waveguides, for example employing a shadowing mask during deposition.

**Applications:**

The proposed solution can be applied to the chip-to-chip optical interconnects for CMOS integrated circuits. With standard device layer thickness of about 220nm, efficient directional coupling cannot take place between a standard optical waveguide having a standard effective index between 1.4 and 1.6. By thinning down some regions of the silicon device layer to an optimal coupling thickness, SOI CMOS chips can be manufactured to enable light coupling to and from an optical waveguide made of a low refractive index material which is used to link two or more CMOS chips. (Figures 5a to 5c)

The proposed solution can be also applied to in / out coupling of an optical signal for high intensity evanescent field biosensors. Such sensors require a high refractive guiding index layer to produce a high intensity evanescent field right above the waveguide layer which the proposed solution provides. Otherwise, in such configurations, butt-coupling to an optical fiber is known to be inefficient.

With reference to Figures 13a and 13b, the proposed solution can be employed to implement an intra-chip inter-layer optical signal transfer between multiple layers. Such structures can be used in microelectronic chips and bioelectronic devices.

With reference to Figures 15a and 15b, the proposed solution can be employed to implement an optical coupling internal to a chip between optical sources and detectors are implemented directly on the chip.
Simplicity of fabrication is one of the advantages of the proposed solution. Very high optical signal injection efficiency into a high refractive index material can be obtained by employing low resolution lithographic techniques. The proposed solution essentially provides a 2D solution to address the problem. Furthermore, this permits employing a large variety of materials, including germanium based semiconductor materials and materials characterized as III-V semiconductors which are useful for optoelectronics.

Another advantage of the proposed solution is derived from a much reduced sensitivity to misalignment (Figure 2e), which is of a great benefit in chip packaging (embedding the chip die in resin).

Another advantage provided by the proposed solution is derived from facet injection (chip edge injection) which permits very easy alignment. This is important because, currently a large fraction of chip component packagers are reluctant to adopt surface injection.

The single inconvenience of the proposed solution stems from polarization dependence. A choice must be made between coupling the incident TM mode or the incident TE mode. Little importance is ascribed to such inconvenience, because many existing low cost solutions can be employed to change the polarization outside of the chip or on chip. For example, in certain applications, this shortcoming can be employed strategically, purposefully, to produce an incident wave separation effect, for example to implement a beam splitter. The polarization dependence can be highly diminished by reducing the width of the high refractive index waveguide to a dimension of the order of that of the thickness thereof.

For certainty while extensive reference has been made to silicon semiconductor waveguides, such reference has only been made for ease of understanding. The invention is not limited to silicon based waveguides and the proposed solution also applies for example to waveguides containing germanium, III-V materials, and others which can be useful for optoelectronics applications.
While the invention has been shown and described with reference to preferred embodiments thereof, it will be recognized by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention as defined by the appended claims.
What is claimed is:

1. An integrated circuit physical optical Input/Output (I/O) interface for coupling at least one mode of an optical signal between a waveguide external to the integrated circuit and a high refractive index waveguide internal to the integrated circuit, the physical optical interface comprising:

   an I/O waveguide conveying an external optical signal near the integrated circuit along an external signal path, said I/O waveguide having a first refractive index; and

   a high refractive index coupler waveguide forming part of the integrated circuit and conveying an internal optical signal along an internal signal path, said high refractive index waveguide having a second bulk refractive index substantially dissimilar from said first refractive index, said high refractive index waveguide having at least a portion with a thickness configured to exhibit an effective refractive index substantially matching said first refractive index of said I/O waveguide, said high refractive index waveguide and said I/O waveguide being arranged substantially parallel and in proximity with an overlap therebetween along said portion having said thickness to permit tunnel coupling of said at least one mode of said optical signal between said internal signal path and said external signal path.

2. An integrated circuit physical optical I/O interface as claimed in claim 1, said high refractive index waveguide comprising a material having a bulk refractive index greater than 2.

3. An integrated circuit physical optical I/O interface as claimed in claim 1, said I/O waveguide comprising a dielectric material having a refractive index lower than 2.

4. An integrated circuit physical optical I/O interface as claimed in claim 1, said I/O waveguide comprising an optical fiber having a core refractive index lower than 2.
5. An integrated circuit physical optical I/O interface as claimed in claim 4, said optical fiber core comprising one of a plastic core and a glass core.

6. An integrated circuit physical optical I/O interface as claimed in any of claims 1 to 5, wherein said I/O waveguide refractive index comprises a refractive index from about 1.4 to about 1.6, and wherein said high refractive index waveguide refractive index is at least about 2.2.

7. An integrated circuit physical optical I/O interface as claimed in any of claims 1 to 6, said high refractive index waveguide thickness being further configured to modify said bulk refractive index to substantially match said I/O waveguide refractive index.

8. An integrated circuit physical optical I/O interface as claimed in any of claims 1 to 7, comprising an optical fiber I/O waveguide having a sufficiently thin cladding providing a tunneling distance at least of a length sufficient to provide coupling with said high refractive index waveguide.

9. An integrated circuit physical optical I/O interface as claimed in any of claims 1 to 7, comprising a waveguide separation layer between said high refractive index waveguide and said I/O waveguide, said waveguide separation layer providing a tunneling distance.

10. An integrated circuit physical optical I/O interface as claimed in any of claims 1 to 9, wherein said coupling is configured to employ evanescent field waveguide coupling.

11. An integrated circuit physical optical I/O interface as claimed in any of claims 8 to 10, said high refractive index waveguide thickness being configured to select one of a TE and a TM incident optical signal polarization.
12. An integrated circuit physical optical I/O interface as claimed in claim 11, said TM optical signal polarization being selected while employing a greater high refractive index waveguide thickness than a high refractive index waveguide thickness necessary to select said TE optical signal polarization.

13. An integrated circuit physical optical I/O interface as claimed in claims 11 or 12, comprising a coupling structure configured for simultaneous TE and TM optical signal polarization coupling.

14. An integrated circuit physical optical I/O interface as claimed in any of claims 11 to 13, said coupling structure being configured to simultaneously couple each of said TE and TM optical signal polarization into corresponding waveguides.

15. An integrated circuit physical optical I/O interface as claimed in any of claims 11 to 14 comprising a signal recombination structure.

16. An integrated circuit physical optical I/O interface as claimed in any of claims 11 to 13, said coupling structure being configured to sequentially couple each of said TE and TM optical signal polarization into a single waveguide.

17. An integrated circuit physical optical I/O interface as claimed in any of claims 1 to 16, said I/O waveguide comprising an intermediary waveguide and an external optical fiber, said intermediary waveguide having an effective refractive index substantially similar to the external optical fiber refractive index.

18. An integrated circuit physical optical I/O interface as claimed in any of claims 1 to 17, said integrated circuit including a layered structure, said layered structure comprising an optical fiber core alignment structure.
19. An integrated circuit physical optical I/O interface as claimed in any of claims 1 to 18, said external optical fiber comprising a circular cross-section cladding, and said alignment structure comprising a V-shaped optical fiber groove.

20. An integrated circuit physical optical I/O interface as claimed in any of claims 1 to 19, said external optical fiber comprising one of: a circular cross-section core and rectangular cross-section core.

21. An integrated circuit physical optical I/O interface as claimed in claims 14 or 16, said coupling structure being further configured to provide said substantially parallel and proximal arrangement over a controlled coupling length providing coupling control.

22. An integrated circuit physical optical I/O interface as claimed in any of claims 1 to 21, said high refractive index waveguide comprising one of: a silicon waveguide, a germanium waveguide, a III-V material waveguide and a semiconductor waveguide.

23. A process for manufacturing a low loss coupler, the process comprising:

   patterning an oxidation mask on top of a device layer; and

   thinning the device layer down to a thickness comprised between 20nm and 200nm in the oxidation mask opened regions.

24. A process as claimed in claim 23, thinning the device layer comprising oxidizing the device layer.

25. A process as claimed in claim 23 or 24, thinning the device layer comprising etching.

26. A process as claimed in any of claims 23 to 25, wherein the oxidation mask comprises silicon nitride.
27. A process as claimed in any of claims 23 to 26, wherein the device layer further comprises one of: silicon, germanium, and a III-V material.

28. A process for manufacturing a low loss coupler, the process comprising:

   fabricating a shadowing mask on top of a high refractive index layer, said shadowing mask having an overhang;

   depositing an etching mask material over said overhanging shadowing mask, said etching mask material forming a taper region under the overhang;

   removing said overhanging shadowing mask; and

   plasma etching both said high refractive index layer and etching mask vertically, said taper region causing said high refractive index layer to be etched non-uniformly forming a tapered structure wherein as said tapered etching mask retreats across said tapered region.

29. A process for manufacturing a low loss coupler, the process comprising employing a shadowing mask during deposition.

30. An optical signal coupler for coupling at least one mode of an optical signal between at least one Input/Output (I/O) waveguide and at least one high refractive index waveguide forming part of an integrated circuit, each of said at least one I/O waveguide conveying an external optical signal along an external signal path, said I/O waveguide having a first bulk refractive index, each said high refractive index waveguide conveying an internal optical signal along an internal signal path, said high refractive index waveguide having at least a portion with a thickness configured to exhibit an effective refractive index substantially matching said first refractive index of said I/O waveguide, said coupler comprising:

   each said second bulk refractive index being substantially dissimilar from said first refractive index; and
at least one alignment structure for positioning said at least one I/O waveguide with respect to said corresponding high refractive index waveguide substantially in parallel, in proximity and with an overlap therebetween along said portion having said thickness to permit tunnel coupling of said at least one mode of said optical signal between said external signal path and said internal signal path.

31. A coupler as claimed in claim 30, said coupler forming part of integrated circuit packaging of said integrated circuit, said coupler being configured as one of:

a complementary structure completing said integrated circuit packaging during assembly; and

an integral structure completing said integrated circuit packaging during wafer level manufacture.

32. A coupler as claimed in claim 31, said complementary structure comprising a snap-on device.

33. A coupler as claimed in claim 32, comprising an external optical fiber corresponding to an I/O waveguide, said coupler being configured to receive said at least one external optical fiber laterally from at least one side of said integrated circuit.

34. A coupler as claimed in claim 33, said at least one external optical fiber comprising a single mode optical fiber conveying a single wave propagation mode, said coupler being configured to preserve said wave propagation mode.

35. A coupler as claimed in any of claims 30 to 34, said integrated circuit comprising a first plurality of high refractive index waveguide bundles, each high refractive index waveguide bundle including at least one high refractive index waveguide, said group of high refractive index waveguide bundles having an array spacing, said coupler comprising:
an array of I/O waveguide bundles, said I/O waveguide bundles array having a spacing corresponding to said high refractive index waveguide bundle spacing; and

a second plurality of alignment structures for positioning said array of I/O waveguide bundles with respect to said corresponding array of high refractive index waveguide bundles, said first plurality being one of: smaller than, equal to and greater than said second plurality.

36. A coupler as claimed in any of claims 30 to 35, each said I/O waveguide comprising:

an intermediary waveguide having said first bulk refractive index; and

a corresponding one of said at least one external optical fiber, said external optical fiber having a core, said first refractive index being substantially similar to an external optical fiber core refractive index, each said optical fiber being configured to convey at least one of: said external optical signal into said integrated circuit and said internal optical signal out of said integrated circuit, said high refractive index waveguides being fabricated flush with an integrated circuit surface.

37. A coupler as claimed in claim 36 comprising:

a butt-coupling between each said external optical fiber and said corresponding intermediary waveguide, and

at least one alignment structure positioning said at least one external optical fiber with respect to said corresponding intermediary waveguide to permit optical signal transmission between said external optical fiber core and said corresponding intermediary waveguide.
38. A coupler as claimed in claim 37, said alignment structure comprising one of at least one bonding contact bead and a V-groove providing a controlled alignment for butt-coupling.

39. A coupler as claimed in any of claims 30 to 35, said I/O waveguide comprising an external optical fiber having a sufficiently thin cladding providing a tunneling distance at least of a length sufficient to provide tunnel coupling with said high refractive index waveguide.

40. A coupler as claimed in any of claims 30 to 39, at least one of said coupler and integrated circuit having a layered structure, said layered structure comprising a waveguide separation layer between said high refractive index waveguide and said I/O waveguide, said waveguide separation layer providing said tunneling distance.

41. A coupler as claimed in any of claims 30 to 40, said waveguide separation layer comprising bonding contact beads providing a controlled tunneling distance.

42. A coupler as claimed in any of claims 30 to 41, said alignment structures comprising at least one of: optical fiber alignment structures and optical fiber cladding alignment features to position said one of said optical fibers with respect to at least one of said high refractive index waveguides.

43. A coupler as claimed in any of claims 30 to 42, said alignment structures comprising a V-groove alignment structure.

44. A coupler as claimed in any of claims 30 to 43, said integrated circuit including a layered structure, said layered structure comprising said at least one alignment structure for positioning one of: said optical fiber, optical fiber core and intermediary waveguide with respect to said high refractive index waveguide.
45. A coupler as claimed in any of claims 30 to 44, said coupler comprising a socket.

46. A coupler as claimed in any of claims 39 to 45, said alignment structures comprising alignment waveguides within said integrated circuit layered structure for butt-coupling a test optical signal during assembly of said socket to said integrated circuit to test alignment.

47. A coupler as claimed in any of claims 30 to 46 wherein said coupling is configured to employ evanescent field waveguide coupling.

48. A coupler as claimed in any of claims 30 to 47, said high refractive index waveguide thickness being configured to select one of a TE and a TM incident optical signal polarization.

49. A coupler as claimed in claim 48, said TM optical signal polarization being selected while employing a greater high refractive index waveguide thickness than a high refractive index waveguide thickness necessary to select said TE optical signal polarization.

50. A coupler as claimed in claim 48 or 49, comprising a coupling structure configured for simultaneous TE and TM optical signal polarization coupling.

51. A coupler as claimed in any of claims 48 to 50, said coupling structure being configured to simultaneously couple each of said TE and TM optical signal polarization into corresponding high refractive index waveguides.

52. A coupler as claimed in any of claims 48 to 50, said coupling structure being configured to sequentially couple each of said TE and TM optical signal polarization into a single high refractive index waveguide.
53. A coupler as claimed in any of claims 30 to 52, said external optical fiber comprising one of: a circular cross-section core and rectangular cross-section core.

54. A coupler as claimed in any of claims 30 to 53, said high refractive index waveguide comprising a material having a bulk refractive index greater than 2.

55. A coupler as claimed in any of claims 30 to 53, said I/O waveguide comprising a dielectric material having a refractive index lower than 2.

56. A coupler as claimed in any of claims 30 to 53, said I/O waveguide comprising an optical fiber having a core refractive index lower than 2.

57. A coupler as claimed in claim 56, said optical fiber core comprising one of a plastic core and a glass core.

58. A coupler as claimed in any of claims 30 to 57, wherein said I/O waveguide refractive index comprises a refractive index from about 1.4 to about 1.6, and wherein said high refractive index waveguide refractive index is at least about 2.2.

59. A coupler as claimed in any of claims 30 to 58, said high refractive index waveguide thickness being further configured to modify said bulk refractive index to substantially match said I/O waveguide refractive index.

60. A coupler as claimed in any of claims 30 to 59, said high refractive index waveguide comprising one of: a silicon waveguide, a germanium waveguide, a III-V material waveguide and a semiconductor waveguide.