Grating-Based Optical Fiber Interfaces for Silicon-on-Insulator Photonic Integrated Circuits

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(Invited Paper)

***Abstract*—In this paper, we review our work on efficient interfaces between a silicon-on-insulator photonic IC and a single-mode optical fiber based on grating structures. Several device configurations are presented that provide high efficiency, polarization insensitive, and broadband optical coupling on a small footprint. The high alignment tolerance and the fact that the optical fiber interface is out-of-plane provide opportunities for easy packaging and wafer-scale testing of the photonic IC. Finally, an optical probe based on a grating structure defined on the fiber facet is described.**

***Index Terms*—Fiber interface, grating couplers, silicon photonics.**

I. Introduction

SILICON photonics is emerging as a very attractive platform to integrate optical functions on a single chip. This has several reasons. First of all, CMOS fabrication tools and processes can be used to realize these devices, much in the same way, as silicon electronic ICs are fabricated. This well-developed technology infrastructure allows realizing low-cost photonic ICs, given the economy of scale and the high yield of the processes. In order to obtain compact photonic ICs, which further reduces the cost of the IC and at the same time also improves the performance of active optoelectronic devices (lower power consumption and larger electrical bandwidth), high refractive index contrast optical waveguide structures should be used, given the high confinement of the optical mode in such a waveguide system. Silicon-on-insulator (SOI) wafers, containing a silicon waveguide layer supported by a buried SiO_2 layer on top of a silicon carrier wafer provide the opportunity to realize optical waveguides with very high omnidirectional refractive index contrast given the large refractive index contrast between silicon ($n \cong 3.45$ in the near infrared) and air or SiO_2 ($n \cong 1.45$). In order to obtain single-mode operation of these silicon strip waveguide structures, the waveguide cross section is deep submicrometer in size, with typical dimensions of 500 nm in width and 200 nm in height. This makes efficient coupling to a standard single-mode fiber far from trivial, given the large mismatch in size between the optical fiber mode and the optical mode propagating in the integrated waveguide. Even the use of end-fire coupling using lensed fibers results in excessive insertion losses, when no integrated spot-size converters are used. Spot-size converters can be implemented in several ways, but the most popular approach—and the one, which lends itself the most to integration in a CMOS process flow—is the use of inverted taper structures with a SiON or polymer overlay. While in this way high-efficiency coupling (insertion losses below 0.5 dB) from a lensed optical fiber to a silicon photonic IC was demonstrated [1], this approach still lacks some features, which are indispensable for low-cost packaging and testing of the photonic IC. Since packaging and testing comprises the largest fraction of the cost of a photonic IC, this is a very important issue. First of all, in order to test a particular photonic IC on an SOI wafer, the wafer needs to be diced and facets need to be polished to achieve a high efficiency, reproducible fiber interface with the photonic circuit. This is, however, a labor intensive, and therefore, costly operation. Moreover, lensed fibers are to be used, since the topography of the spot-size converter (and hence, the SiON/polymer overlay waveguide) needs to be kept to a minimum (typically 2 to 3 μm). Overlay waveguides in this range of thicknesses allow realizing a semicompact inverted taper design, with typical taper lengths on the order of 200 μm. This length increases exponentially however when the spot size is increased. The limitations on the achievable spot size imply that a lensed fiber is still to be used and that the alignment of the lensed fiber to the facet of the photonic IC is very stringent. Active alignment can be used, but again, this is a high-cost solution. In the situation, where multiple fibers in a fiber array need to interface with the IC, the coupling issues become even worse, given the relatively high variations on the fiber pitch in a fiber array and the high cost of lensed fiber arrays.

Therefore, we propose to use grating structures to interface a standard single-mode optical fiber with a photonic IC. These gratings are defined on the surface of the silicon waveguide layer, as shown in Fig. 1. The periodic corrugation of the silicon waveguide core partially diffracts the light that impinges on the

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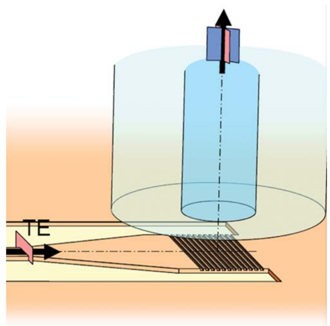


Fig. 1. Basic configuration for a fiber-to-chip grating coupler. A standard single-mode fiber interfaces near vertically with the silicon photonic IC, through a diffractive grating structure defined on the surface of the silicon waveguide.

grating toward the superstrate. Therefore, positioning a standard single-mode fiber (near to) vertically on this grating coupler allows coupling light in and out of the photonic IC. This approach solves the issues mentioned earlier: a waveguide facet is no longer required, which allows wafer-scale testing and packaging. Moreover, when the grating structure is well designed, a standard single-mode fiber can be used to efficiently interface with the photonic IC, with a micrometer-level alignment tolerance. This paper deals with the design and realization of such fiber–chip interfaces. It is organized as follows: in Section II, we will describe the basic operation principle of this type of fiber interface. In Section III, we will describe means to achieve high fiber coupling efficiencies. In Section IV, the optical bandwidth of fiber-chip grating couplers will be described, including multiwavelength band operation of the devices. Section V will deal with polarization handling based on grating structures, since many photonic ICs require polarization independent operation. In Section VI, ultracompact implementations of these fiber interfaces will be presented, while in Section VII, the interfacing to an optoelectronic component will be discussed. Finally, in Section VIII, we will describe an optical fiber probe based on diffractive grating structures that allows probing individual optical components in a photonic IC.

II. Grating Coupler Basics

In its simplest form, a fiber-to-chip grating coupler consists of a periodic structure defined in a waveguide, realized by etching in a high index waveguide layer or by using deposition techniques. Light impinging on the periodic structure will diffract from the grating under an angle determined by the projected Bragg condition, which is graphically illustrated in Fig. 2. The z-component of the wave vector belonging to a certain diffraction order is given by

$$k_{z,m} = \beta + mK$$

in which β is the effective propagation constant of the optical mode in the grating, K is inversely proportional to the grating period Λ, and m is the diffraction order. The actual diffraction angle in the superstrate and substrate is then determined by taking into account the dispersion relation in these media, for

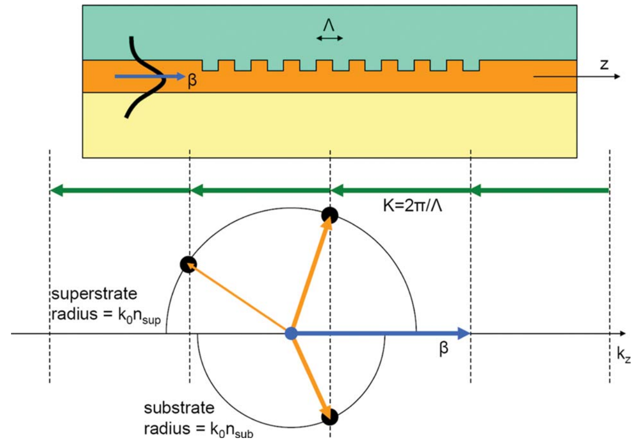


Fig. 2. Cross section through a basic diffraction grating structure and the associated Bragg diagram, graphically illustrating the occurrence of different diffraction orders in superstrate and substrate.

an isotropic medium given by

$$k_{\rm sub,sup} = \frac{2\pi}{\lambda} n_{\rm sub,sup}. \quad (1)$$

By properly designing the grating structure, diffraction can be limited to a single diffraction order. Placing a single-mode fiber under the appropriate angle with respect to the surface of the chip, therefore allows efficient coupling between the optical fiber and the photonic IC. By varying the grating period, the angle of diffraction (and hence, the fiber orientation for efficient optical coupling) can be varied. At first glance, one might prefer to position the optical fiber perfectly vertical with respect to the photonic IC. This requires $K = \beta$. However, this is not a convenient choice, since this also allows another diffraction order to exist when exciting the grating from the optical waveguide, namely

$$k_z = \beta - 2K = -\beta. \quad (2)$$

This implies that this grating structure will provide a strong reflection in the waveguide. While these reflections are as such problematic for many applications, they also result in a drastically decreased fiber-chip coupling efficiency. By properly designing the grating, these reflections can be minimized, e.g., by etching an additional slit in front of the grating structure, which acts as an antireflection coating [2] or by chirping the grating [3]. However, while reflections back into the waveguide can be minimized in this way, still parasitic reflections can occur when using these structures as fiber-to-chip in-couplers rather than grating out-couplers. Therefore, it is more convenient to work in a slightly "detuned" configuration in which the grating period is chosen such that the fiber is tilted slightly off-vertical (with 10° off-vertical being a typical number). In this way, the second-order Bragg reflection is avoided, as can be seen from Fig. 2.

Given the fact that the mode-field diameter of a single-mode optical fiber is about 10 μm, the diffracted field profile needs to have comparable dimensions, implying that a strong (i.e., high-index contrast) grating is required. This can easily be achieved on the SOI waveguide platform. In the remainder of the paper,

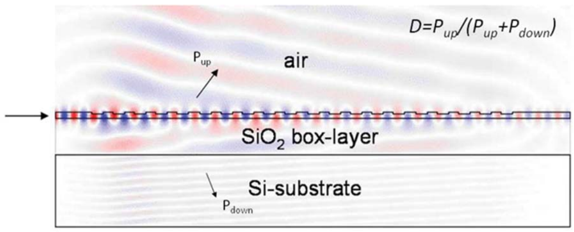


Fig. 3. Rigorous simulation of a diffraction grating defined in a 220-nm-thick silicon waveguide layer, showing the limited directionality of this configuration.

we will focus on this material platform. The grating coupler structures that will be discussed are designed and realized in a 220-nm-thick silicon waveguide layer on a 2-μm-thick buried oxide layer, unless otherwise stated.

While the Bragg formalism discussed earlier allows describing the behavior of diffractive grating structures in first order, in the end rigorous simulation methods are required to fully assess the performance of a grating coupler design. For this, finite-difference time-domain (FDTD) methods or eigenmode expansion methods are used. For simulations, both the fiber mode (grating used as in-coupler) and the waveguide mode (grating used as out-coupler) can be excited. The mode-to-mode coupling efficiency should in both cases, however, be the same, due to reciprocity.

III. High-Coupling Efficiency Gratings

A high-efficiency interface between a standard single-mode optical fiber and a silicon photonic IC is a prerequisite for using grating couplers in practical applications. The coupling efficiency is determined by two factors: first of all, there is the grating directionality D, defined as the ratio of the optical power diffracted toward the optical fiber to the total diffracted power. Second, there is the mismatch between the diffracted field profile and the Gaussian mode of the optical fiber, which results in additional losses. Indeed, in first order, the diffracted field profile originating from a uniform grating can be considered to be exponentially decaying, with a decay length inversely proportional to the grating strength. This implies that there exists an optimal grating strength for which the overlap with the Gaussian fiber mode is maximal. For a fiber-mode-field diameter of 10.4 μm, this optimal field coupling strength is 0.14/μm. For this optimal configuration, the excess loss due to the mode profile mismatch is about –1 dB.

Defining a grating with this close to optimal grating strength can be done by optimizing the grating etch depth or grating fill factor (being the ratio of the etched slit width to the grating period). On a 220-nm silicon waveguide layer, this results in 70-nm-deep slits (with a fill factor of 50%) and a grating period of 630 nm, to allow efficient coupling of 1.55 μm TE polarized light to a standard single-mode fiber, i.e., tilted 10° off-vertical. However, rigorous numerical simulations show that the directionality of such a grating is very poor, resulting in an overall fiber-to-chip coupling efficiency of –5 dB (see Fig. 3). This result implies that optimizing the grating directionality is of paramount importance to maximize the fiber coupling efficiency. In the following, we will describe several strategies to optimize the grating directionality.

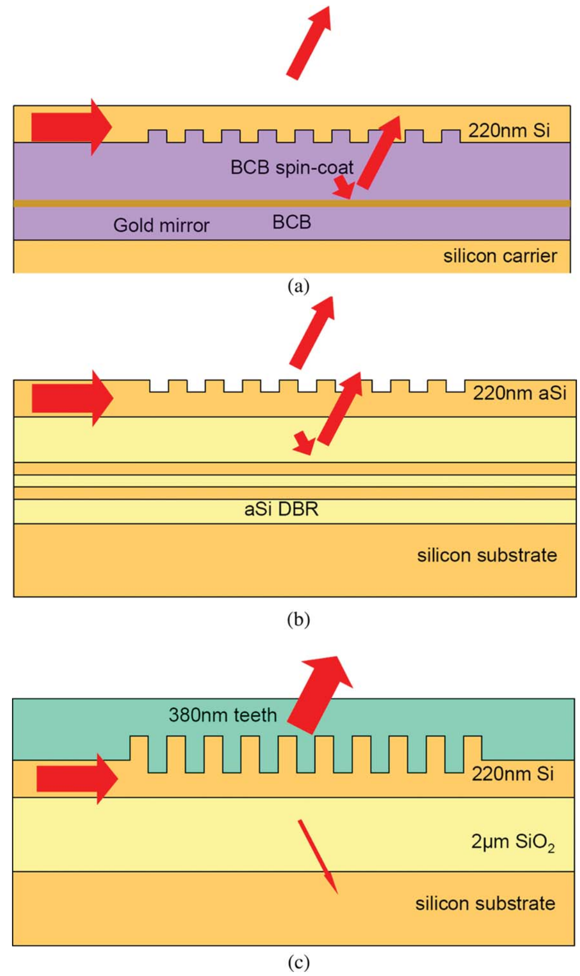


Fig. 4. Strategies to improve the grating directionality: (a) using a bottom metal mirror to redirect the downwards diffracted light, (b) using a bottom DBR mirror and (c) making the grating intrinsically directional by defining a silicon overlay.

A first strategy that can be followed is to optimize the buried oxide layer thickness. Indeed, the light that is diffracted toward the substrate first hits the SiO_2/silicon substrate interface, where a part of the light reflects back toward the grating. By properly optimizing the buried oxide layer thickness, this reflection can interfere constructively with the directly upward diffracted light, thereby leading to a larger directionality. This, however, requires custom SOI waveguide structures, making this approach less practical. Moreover, this approach only moderately improves the directionality, given the limited reflection at the SiO_2/silicon interface.

Therefore, a better approach is to apply a true bottom mirror to reflect close to 100% of the downward diffracted light. This, however, still requires an optimization of the distance between the bottom reflector and the grating layer. This bottom mirror can be realized by means of a metallic layer or a distributed Bragg reflector (DBR), as shown in Fig. 4(a) and (b).

High-efficiency grating structures for the 1550 nm wavelength band were realized using a gold bottom mirror [4] and

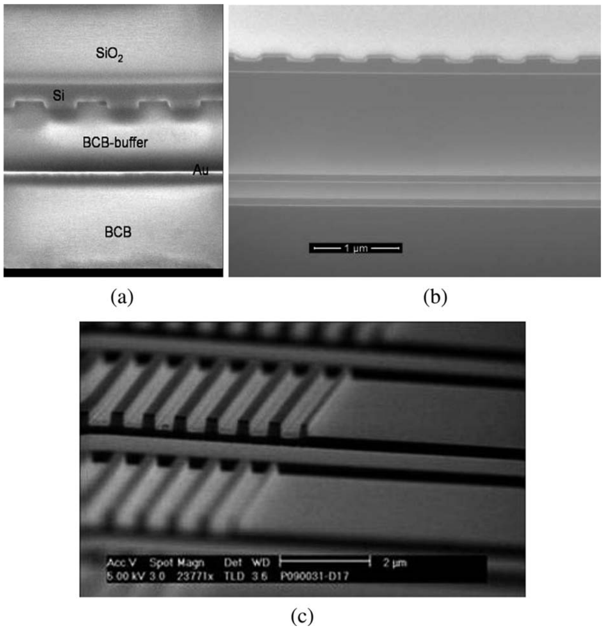


Fig. 5. (a) Scanning electron microscope images of fabricated high-efficiency grating coupler structures based on a metal bottom mirror, (b) an amorphous silicon bottom DBR, and (c) a silicon overlay.

using a two-pair Si/SiO_2 DBR stack [5]. The gold bottom mirror based devices were realized using a divinylsiloxane-bis-benzocyclobutene (DVS-BCB) wafer bonding approach. In this case, the basic grating structures with limited directionality, shown in Fig. 3, were used. On top of these diffraction gratings, a DVS-BCB polymer spacer layer ($n = 1.54$) of 840 nm and a gold mirror of 50 nm were defined, after which the whole device structure was bonded upside-down on a carrier wafer, after which the original silicon carrier wafer was removed in order to access the fiber couplers. The fabricated structures are shown in Fig. 5(a). In this way, –1.6 dB coupling efficiency was obtained for TE polarized light. While these grating structures based on metallic bottom mirrors allow for high-efficiency fiber coupling, the fabrication process is not directly transferable to a CMOS line, since it requires the use of nonstandard bonding processes. Therefore, a Si/SiO_2 DBR-based approach was pursued. The fabricated device structure is shown in Fig. 5(b). The fiber couplers were fabricated on a 200 mm Si wafer. First, a 1-μm-thick SiO_2 isolation layer is deposited on a bare Si wafer. Then, the Bragg mirror, consisting of two 112 nm layers of amorphous silicon and a 267 nm layer of SiO_2 are deposited. On top of the Bragg mirror, 1.48 μm of SiO_2 and a silicon waveguide layer were deposited. Again, the basic grating structure of Fig. 3 was used in order to compare the metallic mirror and DBR mirror approach. The experimentally obtained coupling efficiency is comparable to the metallic mirror approach. A combination of both techniques, i.e., using a DBR mirror on top of crystalline silicon waveguide wafer, which is then transferred to a host substrate is also feasible.

These methods to improve the fiber coupling efficiency are quite complicated in terms of device processing. Therefore, a more elegant solution was proposed, by altering the design of the grating structure such that the grating becomes intrinsically very directional, without the need for "recycling" downward diffracted light [6]. This approach requires the definition of a silicon overlay prior to the etching of the grating, as shown in Fig. 4(c).

The physical principle behind a highly directional grating, as shown in Fig. 4(c), can be understood as follows. Considering the diffracted field pattern as the superposition of the fields emitted by an array of scattering centers (which have a π phase shift with respect to each other for a perfectly vertical coupling grating), constructive interference toward the superstrate (and hence, the optical fiber) can be achieved by realizing an additional π phase shift during the propagation toward the superstrate, since light is propagating either in air (in the etched slit) or in silicon (in the grating tooth). This directionality is thus a function of the waveguide thickness h, the etch depth e in the waveguide, and the silicon overlay thickness o. Furthermore, in order to reach high fiber coupling efficiency, a highly directional grating is required, while at the same time, the grating strength needs to be optimized for maximal overlap with the Gaussian fiber mode. This mode-matching requirement is a function of the same three parameters h, e, and o as the high-directionality condition. Both conditions can be satisfied by optimizing these parameters, thereby resulting in high-efficiency coupling. The fabricated structures are shown in Fig. 5(c). Experimentally, again –1.6 dB fiber-to-chip coupling efficiency is obtained for TE polarized light. This grating structure is intrinsically directional, irrespective of the buried oxide layer thickness [7].

In order to further improve the fiber-chip coupling efficiency, the mismatch between the diffracted field profile and the Gaussian mode profile of the single-mode fiber needs to be reduced. This can be achieved using nonuniform grating structures to gradually change the coupling strength of the grating. This way, in principle, $<$0.5 dB fiber coupling efficiency can be obtained when defining a nonuniform grating on any of the platforms described earlier [8], [9]. Typically, very narrow slits (on the order of tens of nanometers) are required to achieve this goal. This is very challenging for the deep UV lithography tools that are used to define these silicon photonic waveguide circuits on 8-inch SOI wafers. Therefore, we will not consider nonuniform gratings further.

The obtained coupling efficiencies mentioned require an optimization of the fiber position on top of the grating. Alignment tolerances are not very strict however, since one is aligning a single-mode fiber to a spot of about 10 μm in diameter. Experimentally, a –0.5 dB (–1 dB) excess loss alignment tolerance of $\pm$1.5 μm ($\pm$2.5 μm) is obtained. This makes diffractive grating couplers a very attractive solution for the passive alignment of a single fiber or fiber array to a silicon photonic IC. Coupling of a fiber array to a silicon waveguide circuit was reported in [10] and [11].

IV. Grating Coupler Bandwidth

Since the diffraction properties of the grating structure are used to couple light between an optical fiber and the silicon waveguide circuit, the coupling efficiency is inherently wavelength dependent. However, since the considered gratings have a very short coupling length (in order to match the diffracted field size with that of the fiber mode), considerable optical bandwidth can still be obtained. This can be explained by considering the exponentially decaying diffracted field profile as a superposition of plane waves. The angular distribution of these plane waves will become broader when the grating is shorter (and hence, stronger if one assumes that all the light needs to be diffracted from the silicon waveguide over the grating length). This implies that a change in wavelength (implying a rotation of this angular distribution of plane waves) will have a lower impact when the grating is shorter, resulting in a larger optical bandwidth for shorter (stronger) gratings. The exact optical bandwidth depends on the specific design. For the considered high-efficiency grating couplers described in the previous section based on the silicon overlay grating, the –1 dB (–3 dB) excess loss is 45 nm (90 nm) around a wavelength of 1.55 μm.

While this optical bandwidth is sufficient for many applications, there are applications, which require a larger optical coupling bandwidth, especially because of the fact that light in two distinct (and widely separated) wavelength bands needs to be processed by the photonic IC. An important application satisfying this description is the use of integrated transceivers for fiber-to-the-home (FTTH) optical networks, in which at the subscriber side a 1310-nm wavelength is used to transmit upstream data over the network, while a 1490-nm downstream optical signal needs to be processed (and *vice versa* at the central office side). As the wavelength span required in this application exceeds the optical bandwidth of the fiber-to-waveguide grating coupler, an alternative approach is needed, which increases the effective wavelength span, while maintaining the advantage of being compact and allowing wafer-scale testing and ease of packaging.

The concept of fiber-chip coupling using diffraction gratings can, however, be extended to allow two different wavelength bands to interface with the photonic IC. This is illustrated in Fig. 6, showing essentially the same type of grating structures as discussed earlier, however now considering the two access waveguides to the 1-D grating (left and right access waveguide) [12]. By optimizing the grating geometry and the fiber tilt angle, two distinct wavelength bands can be coupled into and out of the waveguide circuit, e.g., the 1310-nm wavelength band and the 1490-nm wavelength band. The maximum fiber-to-chip coupling efficiency that can be obtained in this way is lower than for the case of a single wavelength band, since there is a tradeoff between both wavelength bands. As shown in Fig. 6(c), the coupling efficiency reaches about –2.5 dB for both the 1310 and 1490 nm wavelength band, with a –3 dB excess loss bandwidth of 55 to 60 nm for the silicon overlay design. These grating structures couple two wavelength bands to the silicon waveguide circuit, while at the same time spatially separating them on the chip. Therefore, this type of grating is also referred to as a grating duplexer.

These duplexing grating structures, as well as the 1-D grating structures described in Section III, perform very differently for TE and TM polarized light. This is an intrinsic problem for high index contrast waveguide structures. In many practical applications (such as the FTTH application mentioned earlier), However, polarization independent operation is required. This will be discussed in the following section.

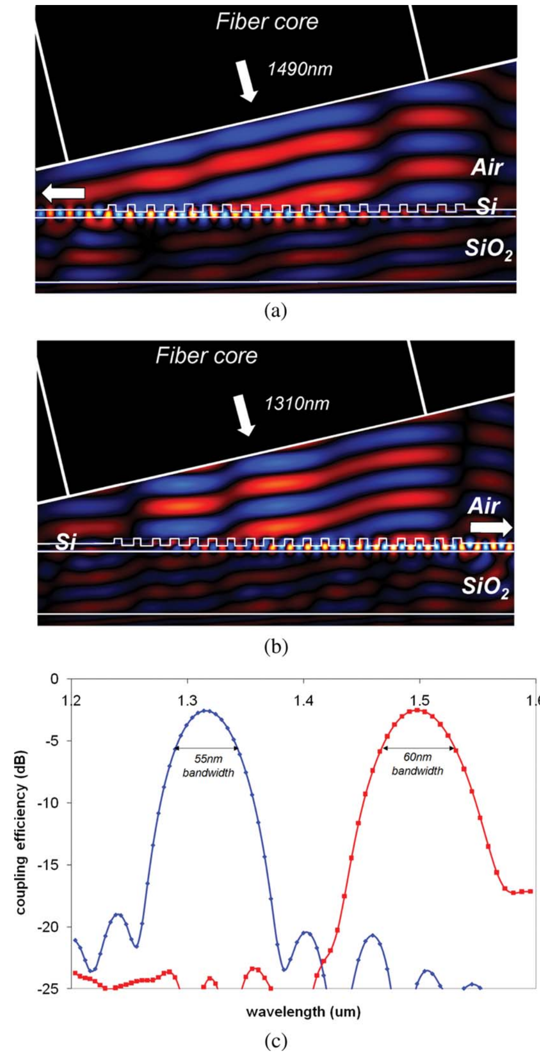


Fig. 6. One-dimensional grating duplexer design operating in the 1.3 and 1.49 μm wavelength range: (a) coupling of 1490 nm wavelength TE polarized light to the silicon waveguide circuit, (b) coupling of 1310 nm wavelength TE polarized light to the silicon waveguide circuit, and (c) coupling efficiency spectrum for the optimized structure.

V. Polarization Handling

High index contrast and high-confinement waveguide structures are intrinsically very polarization dependent. This implies that realizing an intrinsically polarization independent photonic IC on the SOI platform discussed in this paper is nearly impossible. However, the problem of polarization handling can be solved by using a polarization diversity configuration. In this configuration, the two orthogonal polarizations in the optical fiber are both coupled to the photonic IC, but into a different waveguide. Thereby, the two polarizations are split on the chip and can be further processed by two parallel photonic ICs. This implies that polarization independent operation can be achieved, at the expense of doubling the size of the IC. Polarization

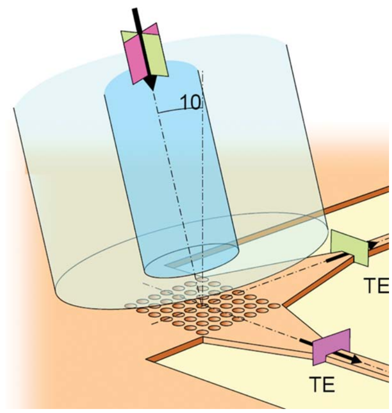


Fig. 7. Two-dimensional grating coupler for polarization handling on a silicon photonic IC.

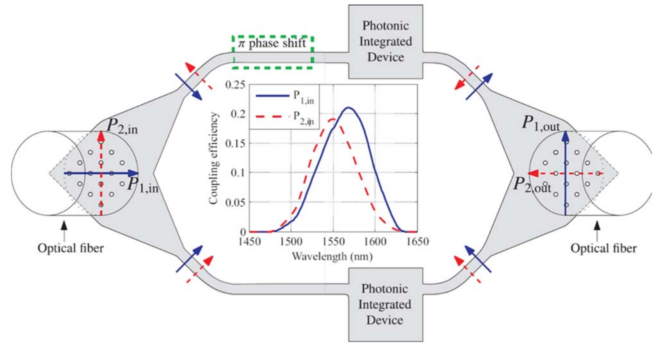


Fig. 8. Polarization diversity waveguide circuit with an introduced π phase shift to eliminate residual polarization dependent loss originating from the tilting of the optical fibers

diversity can be implemented very elegantly using diffraction grating structures. Both 1-D and 2-D diffraction gratings can be used for this purpose.

The operation principle of a 2-D grating structure is outlined in Fig. 7, showing how a square lattice of holes (that can be considered as the superposition of two orthogonal 1-D grating structures) efficiently couples both orthogonal polarizations to the chip. The coupling is such that the orthogonal polarizations in the optical fiber are coupled to essentially identical polarizations (in our case TE) in two orthogonal waveguides. This 2-D grating structure, therefore, at the same time performs the function of a fiber–chip interface, a polarization splitter and polarization rotator for a polarization diversity approach, all on a 10 μm-by-10 μm footprint.

Experimental realizations of these 2-D structures, by etching a square lattice of holes 70 nm deep into the silicon waveguide layer show intrinsically the same efficiency as the standard 1-D grating structures, as shown in Fig. 3. Quasi-polarization independent operation was obtained in a 10-nm wavelength range around the grating coupler coupling efficiency maximum (below 1 dB polarization dependent loss) [13]. Outside this wavelength range, the polarization dependent loss becomes too high for practical purposes. The origin of the residual polarization dependent loss and the strong wavelength dependent behavior is the tilting of the optical fiber. In case, the fiber is positioned perfectly vertically on top of the 2-D grating structure, the polarization dependent loss is intrinsically zero (provided that the optical fiber is well aligned on the grating structure). As discussed in Section II, the perfectly vertical orientation of the optical fiber is however not convenient due to the presence of second-order Bragg reflection. Therefore, the fiber is tilted off-vertical, along the bisection line of the 2-D grating structure, as shown in Fig. 7. This configuration is schematically outlined in Fig. 8, illustrating the use of 2-D gratings in a polarization diversity scheme with an off-vertical fiber interface [14]. Two orthogonal polarizations in the optical fiber P_1 and P_2, where P_1 lies along the bisection line of the photonic IC are to be considered. In case the optical fiber is perfectly vertical, both polarizations experience the same fiber coupling efficiency. Polarization P_1 equally excites the TE-polarized waveguide mode in the upper and lower waveguide arm and both are excited in phase. For polarization P_2, the TE-polarized waveguide modes in both waveguide arms are also excited equally, however, this time with a π phase shift between both arms of the polarization diversity circuit. When the optical fiber is now tilted off-vertical, along the bisection line of the polarization diversity circuit, polarizations P_1 and P_2 will no longer experience the same fiber–chip coupling efficiency, since polarization P_1 is tilted out of plane. This is shown in the inset of Fig. 8 (result of 3-D FDTD simulations). This tilting of the optical fiber, therefore, leads to an intrinsic polarization dependent loss of the 2-D grating coupler. An elegant way to circumvent polarization dependent loss (PDL) for fiber-to-fiber connected photonic ICs is to introduce an additional π phase shift between both arms of the photonic IC. Indeed, adding this π phase shift renders the TE modes excited by polarization P_2, which were initially out of phase, in phase at the 2-D grating out-coupler. This implies that these modes will recombine in the output fiber as polarization P_1, and *vice versa* for the other polarization state. The implication of this π phase shift is therefore that, when looking at the fiber-to-fiber transmission spectrum, both polarizations experience once the fiber–chip coupling curve for polarization P_1 and P_2, thereby eliminating the polarization dependent loss originating from the tilt of the optical fiber. This was experimentally verified by applying a heater on top of one arm of the polarization diversity circuit, as shown in Fig. 8, to introduce a phase shift between both arms. At the same time, the polarization dependent loss of the circuit (which was in this case, a simple ring resonator waveguide circuit) was monitored. Low polarization dependent loss in this type of polarization diversity circuit however also relies on the fact that the actual photonic ICs in both arms of the polarization diversity configuration need to be identical. This is far from trivial in high index contrast waveguide circuits, even using state-of-the-art fabrication technologies. For example, if the waveguide width of a SOI ring resonator varies by 1 nm, also the resonance wavelength of the resonator shifts by approximately 1 nm. This implies that we typically will also need to be able to trim both waveguide circuits to make them truly identical. In some circuit configurations, this problem can be circumvented by using a single photonic IC in which light propagates in opposite directions [15]. In Fig. 9, we plot the

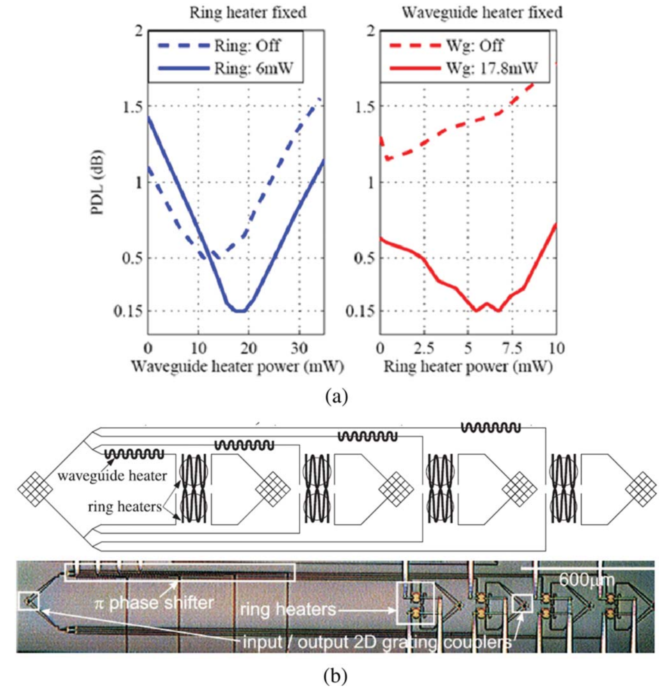


Fig. 9. Influence of the waveguide heater power and ring resonator heater power on the residual PDL of the polarization diversity waveguide circuit (a) shown in (b).

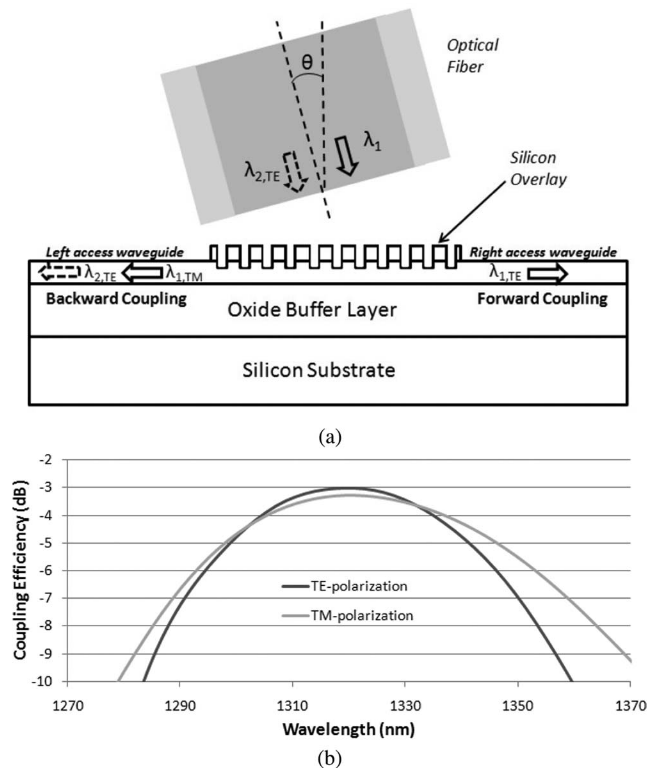


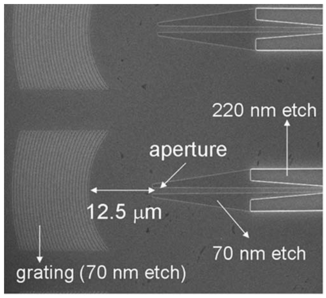
Fig. 10. One-dimensional grating configuration for a polarization diversity waveguide circuit, allowing polarization independent handling of a single wavelength band (λ_1), while also accommodating coupling of a second wavelength band (λ_2) for a single polarization: (a) device layout and (b) coupling spectrum for the polarization independent wavelength band λ_1.

residual polarization dependent loss for a varying waveguide heater power (i.e., phase shift) and for a varying ring resonator heater power (used to trim the ring resonator to make both arms of the polarization diversity circuit identical). Indeed, a large reduction in polarization dependent loss can be observed, from 1.5 dB without any heater control, down to 0.15 dB in the optimal configuration. Low PDL values (i.e., below 1 dB) for a given waveguide heater and ring heater power dissipation can also be obtained over a larger wavelength range (i.e., 25 nm).

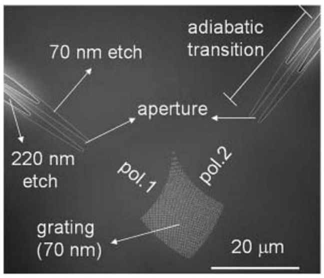
A second implementation of a grating structure for a polarization diversity configuration is based on a 1-D line grating structure. Line grating structures have the advantage that they can be optimized more easily than square lattice grating structures (given the quasi-2-D behavior of the line gratings), and hence, ultimate performance can be expected from these devices. The configuration that is considered is shown in Fig. 10(a). Again, both access waveguides to the 1-D grating structure are used and a silicon overlay is used to boost the efficiency of the grating structure. The operation principle is comparable to the grating duplexer described in Section IV, except now the TE and TM polarizations at the same wavelength are considered (compared to the TE polarized modes at two different wavelengths for the grating duplexer) [16], [17]. Proper design of the grating allows for quasi-identical fiber-to-chip coupling efficiencies for both polarizations over a limited wavelength range, hence resulting in a low-polarization dependent loss of the 1-D grating structure, as shown in Fig. 10(b), in this case, for the 1310-nm wavelength band. Also experimentally, a low PDL was obtained, i.e., from 1240 to 1310 nm, the fiber-to-fiber PDL is lower than 1 dB, which covers 42 nm within the 50 nm –3 dB coupling efficiency bandwidth of the grating coupler [17]. Since the device configuration is identical to the grating duplexer configuration described in Section IV, an additional wavelength band λ_2 can be accommodated, although only for a single polarization. In order to build true polarization diversity circuits based on these 1-D grating couplers, an additional polarization rotator is required to obtain identical polarizations in both arms of the circuit. Several implementations of a polarization rotator on the silicon waveguide platform can be considered [18], [19].

VI. Ultracompact Implementations

The diffraction grating structures considered in this paper are very compact, since they only occupy the area of the core of a standard single-mode optical fiber, roughly 10 μm-by-10 μm. However, in order to convert the 10-μm-wide optical waveguide mode to that of a 0.5-μm single-mode waveguide, a relatively long adiabatic taper is required, on the order of 150 μm in length. This makes the total device structure less compact, thereby increasing the overall footprint of the photonic IC. One elegant way to circumvent this issue is to use focusing grating structures, instead of the waveguide structures described earlier. A 1-D grating structure can be made to focus the coupled beam on a micrometer size aperture by curving the grating lines, as shown in Fig. 11(a) [20], [21]. In this case, each grating line represents a part of an ellipse, while all ellipses describing the focusing grating have a common focal point, namely at the wave-

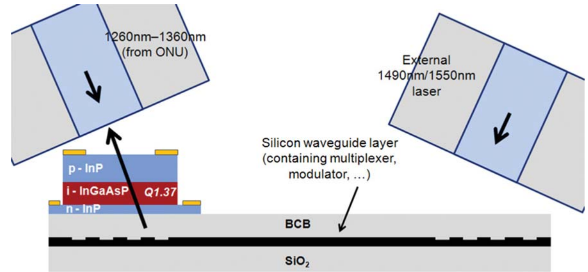


(a)

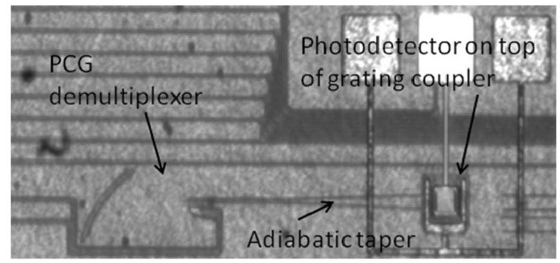


(b)

Fig. 11. (a) One-dimensional (a) and (b) 2-D curved gratings as ultracompact grating coupler structures.



(a)



(b)

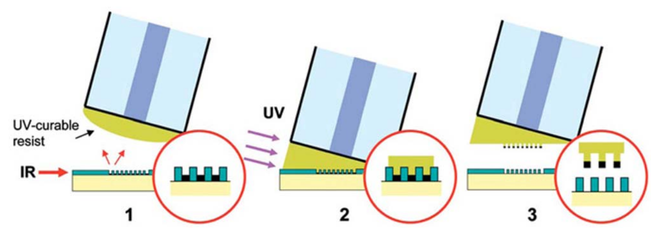
Fig. 12. Example of the integration of a photodetector on top of a diffractive grating coupler: (a) schematic device layout and (b) microscope image of the fabricated structure.

guide aperture. A similar design consideration can be made for 2-D grating couplers, by considering them as a "superposition" of two 1-D curved grating structures. This way a 2-D grating structure can be designed by implementing a scattering center (i.e., an etched hole) at the intersection of the two orthogonal curved 1-D gratings. This approach can dramatically decrease the overall footprint of the device, as shown in Fig. 11(b) (in this case for the standard grating configuration of Fig. 3), without impacting the overall performance of the device in terms of fiber coupling efficiency, alignment tolerance, and polarization dependent loss.

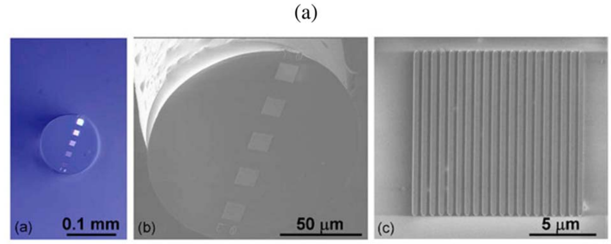
VII. Interfacing to Optoelectronic Components

So far, the grating structures were considered as an efficient interface between a silicon photonic IC and a single-mode optical fiber. However, its use can be extended to also interface with optoelectronic components (lasers, photodetectors, etc.) integrated on the silicon platform. It is easy to envision the integration of a III–V semiconductor photodetector on top of a grating coupler, either through flip-chip integration or heterogeneous integration. An example of such a heterogeneously integrated III–V/silicon device is shown in Fig. 12 [22], [23]. In this case, a III–V epitaxial layer stack is transferred to a silicon waveguide circuit by means of a BCB adhesive bonding process [24]. This silicon waveguide circuit contains diffraction gratings for vertical interfacing with both an optical fiber and the photodetectors defined in the III–V epitaxial layer.

Besides interfacing with photodetectors, also the coupling of laser emission into the photonic IC can be envisioned. This is, however, complicated by the fact that the laser beam needs to be coupled in near-vertically (but not perfectly vertical) in order to be efficiently coupled to the waveguide circuit. This requires either microoptics (reflecting mirrors or refractive wedges) or a tilted mounting of the laser.



(a)



(b)

Fig. 13. Fabrication procedure to define a gold grating on a single-mode fiber facet: (a) schematic of the fabrication procedure and (b) microscope images of the fabricated gratings on the fiber facet for different zooms.

VIII. Optical Fiber Probe

One very attractive feature of grating couplers is that they allow interfacing with a photonic IC on a wafer scale. This allows for wafer-scale testing and packaging of the photonic IC. However, one would often want to be able to probe individual optical components of a complex interconnected silicon photonic IC, e.g., for debugging purposes. This can be achieved using an optical fiber probe, in which the diffractive grating structure is defined on the facet of a single-mode optical fiber [25].

In Fig. 13(a), the method to define this grating structure is outlined. A gold grating was defined on a fiber surface using a nanoimprint technique. First, the fiber with UV-curable resist is aligned over the specially prepared mold carrying the 10-by-10 μm gold grating pattern in the trenches of the mold. Upon attachment, the cavities are filled and the resist is UV cured. Finally, the mold is released. The metal grating is now attached to the fiber, due to the fact that the mold was covered with an antistiction film prior to gold deposition. By using gold as the grating material, a high-refractive index contrast is obtained. A fabricated optical probe is shown in Fig. 13(b). This way efficient coupling between the optical probe and the photonic IC can be obtained. Experimentally, 15% coupling efficiency between a single-mode fiber probe and a 3-μm-wide photonic IC was realized for TE polarized light at 1.55 μm wavelength. The grating consisted of 20-nm-thick gold stripes on a 630 nm pitch. The realization of this optical probe can pave the way to wafer-scale testing of high index contrast large-scale integrated waveguide circuits.

IX. Conclusion

Photonic ICs have tremendous benefits over their discrete counterparts. Especially, the use of high index contrast waveguide structures for photonic ICs allows large-scale integration of optical functions on a single substrate, reducing the cost, size, and weight of the devices, while improving their performance. Silicon photonics is emerging as a very promising platform for photonic integration, since the economy of scale in fabrication will make the photonic ICs virtually free. The cost of the packaging and testing of these ICs is therefore the predominant cost and performance issue, and is therefore one of the most important aspects for bringing high index contrast waveguide structures from research to practical applications. In this paper, we show that the use of diffractive grating structures could provide a low-cost solution for this problem, since wafer-level testing and packaging can be realized without the need for polished facets.

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