Interfacing optical fibers and high refractive index contrast waveguide circuits using diffractive grating couplers

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ABSTRACT

The interfacing of an optical fiber and a photonic integrated circuit becomes more complex on a high refractive index contrast waveguide platform due to the large mismatch in mode size between the optical fiber mode and the waveguide modes in the integrated circuit. In this paper we review our work in the field of diffractive grating structures, in order to realize a high efficiency, polarization independent, large bandwidth optical interface with high index contrast waveguides fabricated on the silicon-on-insulator platform.

Keywords: Diffractive gratings, Silicon-on-Insulator, fiber interface

1. INTRODUCTION

The large scale integration of optical functions on a photonic integrated circuit is a long standing goal. This requires a high refractive index contrast waveguide platform to realize the optical functions in, as high refractive index contrast structures allow making wavelength-scale optical functions, which are interconnected by ultra-compact optical waveguides, which can be routed using bends with wavelength scale radii. The use of a high refractive index contrast waveguide platform however compromises the interfacing of the photonic integrated circuit with the outside world, i.e. a single mode optical fiber. This is due to the large mismatch in size between a high index contrast waveguide mode (typically on the order of $0.1\mu m^2$) and the mode of a single mode optical fiber (with a core diameter of 9µm). Mere butt-coupling of the photonic integrated circuit and the single mode optical fiber would lead to unacceptably high coupling loss for practical applications. Therefore, a lot of effort is devoted to reduce this coupling loss. This can be achieved by converting either the size of the optical waveguide mode or optical fiber mode using adiabatic taper structures [1]. This allows a broadband, high-efficiency optical coupling but it requires however lengthy adiabatic taper structures and/or specialty optical fibers. But most of all it requires a polished facet at the waveguide circuit to interface with the optical fiber. This approach prevents testing the photonic integrated circuits on a wafer-scale prior to die singulation. If wafer-scale testing is a requirement, the optical fiber should interface with the photonic integrated circuit from the top of the wafer surface, requiring a deflection mechanism to couple light between the high index contrast waveguide structure and the single mode optical fiber. In this paper we shall focus on the use of diffractive grating structures to interface the high refractive index contrast waveguide structure with a single mode optical fiber. It will become clear throughout this paper, that the use of diffractive grating structures provides an elegant, high coupling efficiency, large optical bandwidth, polarization independent optical coupling scheme, which is compatible with planar fabrication technology.

2. DIFFRACTIVE GRATING STRUCTURES

The diffractive grating structures considered in this paper are defined on top of a layer structure with high vertical refractive index contrast, such as in the case of the silicon-on-insulator material system, in which the light is guided in a thin (about $\lambda/2n$ thick in order to be single mode) silicon waveguide layer (n=3.45), separated from the silicon substrate by a buried SiO_2 layer (n=1.45). In their most basic form these grating structures consist of local periodic changes in the refractive index in the vicinity of the waveguide structure. This can be achieved by etching the surface of the waveguide

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layer, or by depositing a periodic structure on top of the waveguide structure. The diffraction of light in these waveguide grating structures can be described by the projected Bragg condition

$$k_{//,ij} = \beta_m + iK_1 + jK_2$$

in which $k_{//,i}$ represents the projected component of the wave vectors of the diffracted waves. β_m is the propagation constant of the waveguide mode in the periodic grating structure and $K_{1,2}$ is related to the periodicity of the diffraction structure by

$$K_{1,2} = \frac{2\pi}{\Lambda_{1,2}} e_{1,2}$$

in which $\Lambda_{1,2}$ is the period of the grating in direction $e_{1,2}$ (two directions of periodicity occur in two-dimensional surface grating structures). These projected components of the diffracted waves determine the number of diffraction orders occurring in a periodic structure and also determine the angle of diffraction θ, as the wave vector of the diffracted wave should satisfy the dispersion relation in the superstrate (or substrate):

$$k = \frac{2\pi}{\lambda} n_{\sup} = \sqrt{k_{//}{}^2 + k_{\perp}{}^2} = \frac{k_{//}}{\sin(\theta)}$$

This is schematically illustrated in figure 1. The Bragg condition is only valid in infinitely extending periodic structures. In this paper we will consider high refractive index contrast gratings with a length of about 10µm to interface with a single mode optical fiber, so the Bragg condition is only indicative for the actual behavior of the diffraction grating. While the Bragg condition describes the direction of the diffracted beam, the diffraction efficiency towards a certain diffraction order remains to be assessed using rigorous methods such as FDTD or eigenmode expansion.

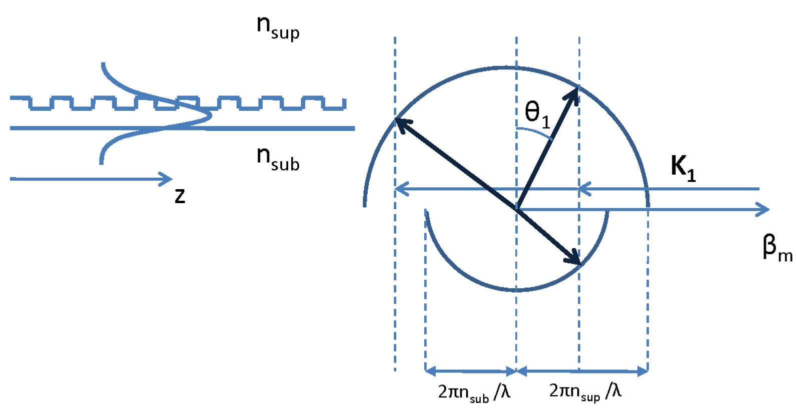

Fig. 1. Bragg vector diagram illustrating the diffraction properties of a periodic structure.

3. ONE-DIMENSIONAL GRATING COUPLERS

3.1 Single wavelength band one-dimensional diffraction gratings

The most basic grating structure that can be used to interface with a single mode optical fiber is a one-dimensional diffraction grating. This grating can defined in several ways on the high index contrast waveguide structures. In our work five types of one-dimensional grating couplers were studied, which are schematically outlined in figure 2. In figure 2a, the grating coupler is defined by directly etching a periodic structure in the high refractive index waveguide core [2]. In figure 2b, the grating structure is etched into a thickened waveguide layer, which gives more flexibility in terms of design [3]. Another option that was investigated (figure 2c) is the inclusion of a metallic bottom mirror to redirect the downwards diffracted light towards the optical fiber [4]. While these gratings are defined by etching the high refractive index core of the waveguide layer, in figure 2d, the grating is defined by creating a metallic periodic structure on top of the waveguide core [5]. In figure 2e, a slanted grating structure is considered in order to increase the directionality of the grating, by applying these angled slots in a frustrated total internal reflection regime [6]. As these one-dimensional grating structures are defined on a high refractive index waveguide platform, they are inherently very polarization dependent. In the following therefore only transverse electric polarized light will be considered with the electric field parallel to the grating lines. Polarization independent operation will be discussed in section 3.

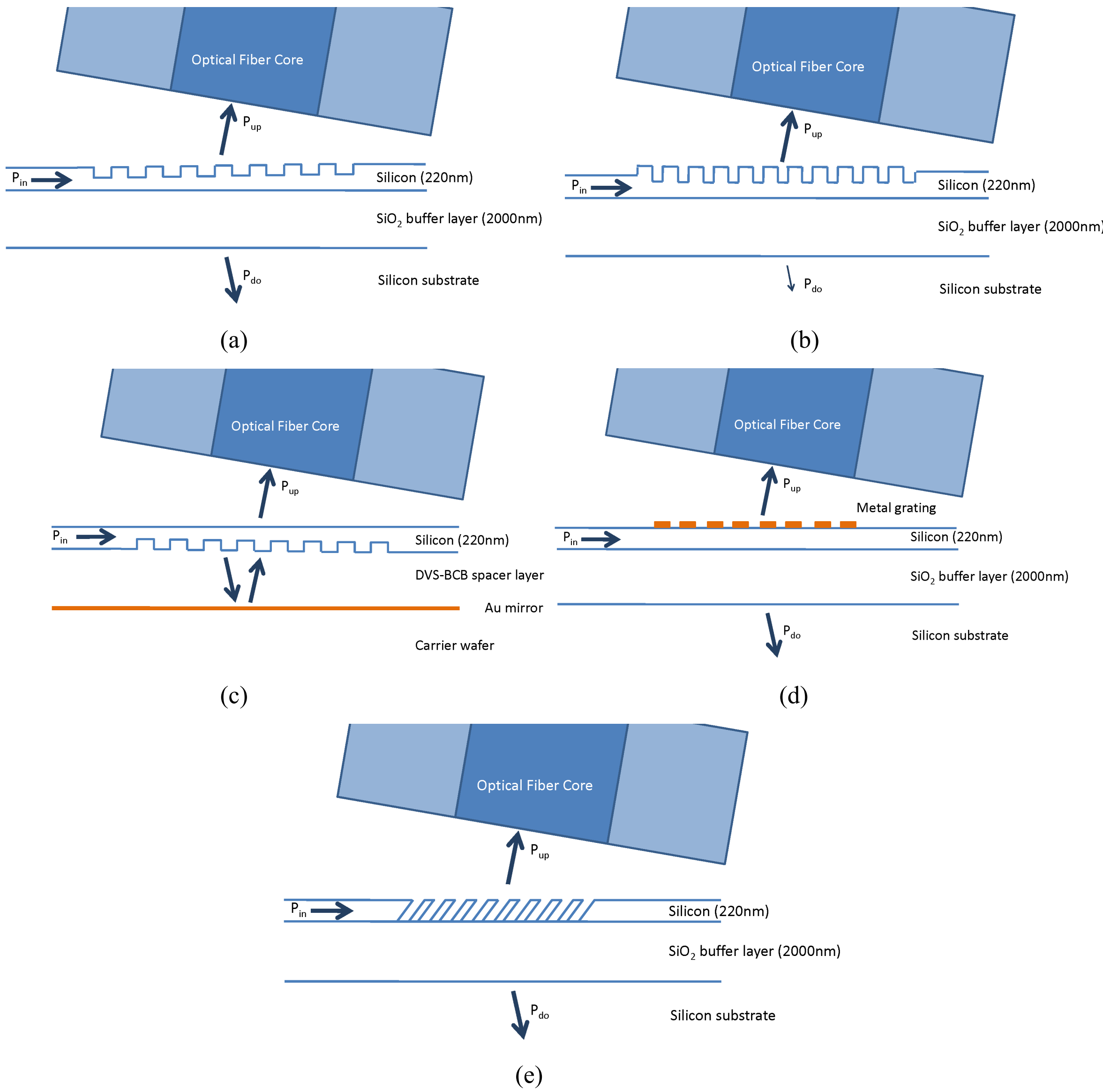

Fig. 2. Studied one-dimensional diffractive grating structures: directly etched gratings (a), raised fiber couplers (b), metallic bottom mirror gratings (c), metallic periodic structures (d) and slanted grating couplers (e).

While the exact properties of the high index contrast gratings have to be assessed by numerical methods, a perturbation method can be used to gain insight in the performance limitations of uniform diffraction gratings. When exciting the waveguide grating by the waveguide mode, in a perturbation analysis the diffracted field in the superstrate can be written as an exponentially decaying function. As the mode of the optical fiber has a Gaussian field profile, inherently there is a mismatch between both mode profiles, limiting the coupling efficiency as shown in figure 3. It also implies that there is an optimum grating strength α of about 0.14/µm for optimal coupling with a Gaussian fiber (which has a $1/e^2$ mode field diameter of 10.4µm). Besides the grating coupling strength also the directionality *D* (being the ratio of the optical power that is diffracted towards the optical fiber compared to the total of diffracted power) of the grating structure needs to be optimized in order to achieve maximum coupling efficiency. Based on these arguments one can deduce that the optimum coupling efficiency from a uniform diffraction grating to a single mode optical fiber is *0.81D* as shown in figure 3. The mismatch between the exponential decaying diffracted field and the Gaussian mode profile can be reduced by designing non-uniform diffraction gratings, improving the coupling efficiency to about *D*. Non-uniform grating structures however complicate fabrication and are therefore outside the scope of this paper.

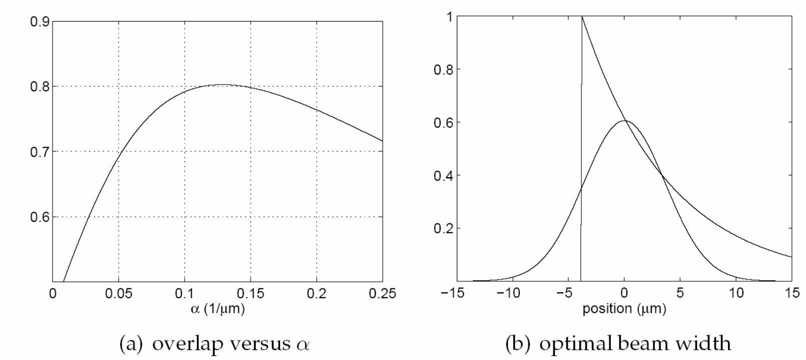

Fig. 3. Overlap of the Gaussian fiber mode and the exponentially decaying diffracted field profile (normalized by the directionality *D)*

A scanning electron microscope image of each of the proposed diffractive grating structures is presented in figure 4. In figure 4a, the grating is directly etched in the 220nm thick SOI waveguide layer. The grating period is 630nm, the etch depth 70nm and the grating fill factor is 50%, leading to diffraction under an angle of about 10 degrees in a wavelength range around 1550nm, which implies that the optical fiber has to be tilted 10 degrees off the surface normal. This tilt is required to avoid a strong second order Bragg diffraction, which would lead to high reflection in the waveguide and decreased fiber coupling efficiency. The fiber coupling efficiency versus wavelength is plotted in figure 4b, illustrating -5dB fiber coupling efficiency, with a 1dB optical bandwidth of 45nm. The fiber coupling efficiency critically depends on the thickness of the buried oxide layer, as the reflection at the SiO_2/silicon substrate interface of the downwards diffracted light can interfere destructively or constructively with the upwards diffracted light, thereby changing the directionality *D* (and the coupling strength of the grating). By changing the buried oxide layer thickness the fiber coupling efficiency (for this particular grating design) can vary from -7.5dB to -2.5dB.

In order to increase the fiber coupling efficiency without tweaking the buried oxide layer thickness (as these "optimal" SOI wafers are not always available), the diffraction grating needs to be made inherently more directional. This can be achieved by thickening the silicon waveguide layer where the grating will be etched by silicon epitaxy or amorphous silicon deposition. This increases the degrees of freedom in designing the grating structure in order to obtain higher directionality. In figure 4c, a cross-section of a realized raised fiber coupler is shown, in which 180nm of silicon was epitaxially grown on top of a 220nm thick SOI waveguide. After epitaxial growth a uniform grating with a grating period of 610nm, an etch depth of 230nm and a grating duty cycle of 50% was defined. Experimentally, -2.6dB fiber coupling efficiency was obtained with a 1dB optical bandwidth of 50nm as shown in figure 4d [7]. This is close to the theoretical value obtained by full vectorial calculations. In the experiment index matching fluid was applied between the SOI grating and the optical fiber in order to avoid reflections at the fiber facet. While only a moderate improvement of the coupling efficiency is obtained in this way, simulations show that changing the duty cycle of the grating can have a serious impact on the obtainable fiber coupling efficiency. A uniform grating with a silicon overlay of 180nm, a grating period of 705nm, a grating etch depth of 280nm and a grating duty cycle (defined as the ratio of the grating slit width to the grating period) of 80% shows a fiber coupling efficiency up to -1dB at 1550nm for a 10 degree tilted optical fiber. Another way to improve the directionality of the diffraction grating is to incorporate a bottom mirror. A realization of the integration of a gold bottom mirror by means of wafer bonding is shown in figure 4e. In this case a standard grating (as the one in figure 4a) is defined on an SOI wafer, after which a polymer spacer layer is applied onto which a gold mirror is deposited. After deposition of the gold mirror the SOI waveguide circuit is bonded onto a carrier (a Pyrex carrier in this case), after which the silicon substrate of the SOI wafer is removed using mechanical grinding and wet chemical etching using KOH, using the buried oxide layer as an etch stop layer. In this way the grating structure is accessible with an optical fiber. In figure 4f, the fiber coupling efficiency is plotted as a function of wavelength, showing that -1.5dB fiber coupling efficiency is obtained, with a 1dB optical bandwidth of 40nm. As in the case of the standard grating structure, the distance between the gold mirror and the diffraction grating strongly influences the obtainable fiber coupling efficiency, as it determines the phase relation between the directly upwards diffracted beam and the beam that reflects on the bottom mirror. Besides fabricating the diffractive grating structure by etching the silicon waveguide layer, a high index contrast grating can also be obtained by depositing a metallic periodic structure on top of the waveguide. An experimental realization is shown in figure 4g, where a 20nm thick gold grating is deposited on an SOI waveguide wafer by means of lift-off. The coupling efficiency spectrum is shown in figure 4h. The obtained coupling efficiency and 1B bandwidth is comparable to the case of the standard grating structure shown in figure 4a. This gold diffractive grating structure allows creating a plasmonic waveguide platform in which both the plasmonic waveguides and the fiber coupling structures are realized in the same processing step. In figure 4i, a scanning electron microscope cross section image of a slanted grating coupler is shown. This structure was fabricated using Focused Ion Beam (FIB) technology. The slanted structure is designed to improve the directionality of the grating. By choosing sufficiently narrow grating slits, light can be coupled out in a distributed way due to the frustrated total internal reflection at the slanted silicon/air interface. Experimentally -3.3dB coupling efficiency was obtained.

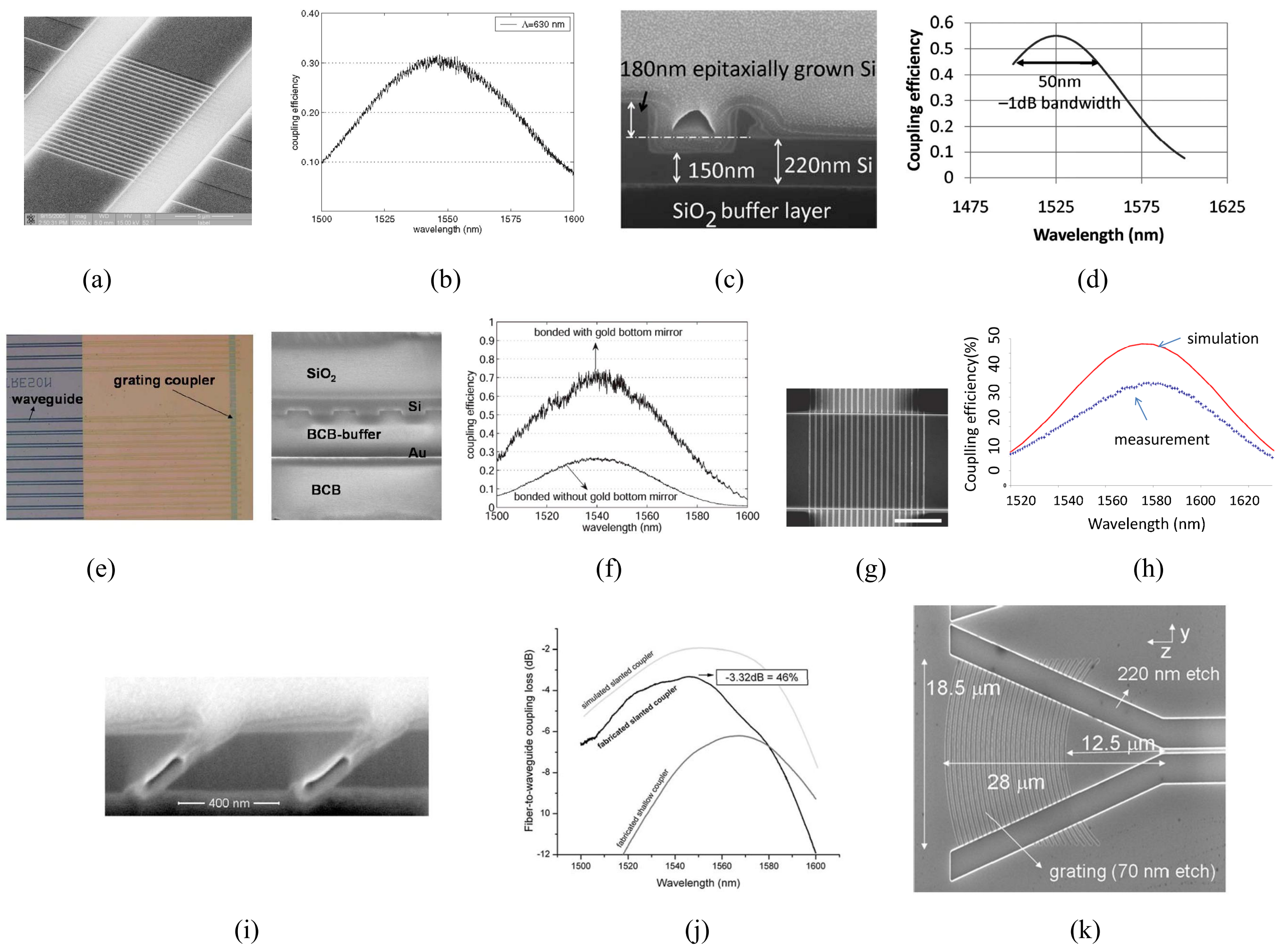

Fig. 4. Overview of experimentally realized one-dimensional diffraction grating structures to interface with a fiber

While these one-dimensional grating structures only occupy approximately 10µmx10µm to interface with a single mode optical fiber, still a relatively long (>100µm) adiabatic taper is required to laterally convert the size of the optical mode to that of a single mode silicon waveguide. A more elegant and compact way of realizing this interface is by implementing curved one-dimensional gratings, which do not only diffract the light in the silicon waveguide layer, but at the same time also focuses the light to a diffraction limited spot. This way, long adiabatic tapers can be avoided, while not compromising the coupling efficiency. This is illustrated in figure 4k, showing an experimental realization of a focusing grating coupler (in the configuration of figure 2a). The experimentally obtained fiber coupling efficiency is comparable to the linear grating structures [8].

3.2 Double wavelength band one-dimensional diffraction gratings

While the diffraction gratings discussed above show a 1dB bandwidth of about 40 to 50nm, in a number of applications a wider span of input wavelengths should be addressed by the photonic integrated circuit. This is especially the case for a transceiver application in which the 1300nm and 1550nm wavelength band are used for upstream and downstream communications. In order to extend the wavelength range in the case where two distinct wavelength bands need to interface with the photonic integrated circuit, the intrinsic diffraction properties of the grating can be used to address this issue, as shown in figure 5a. In this case the diffraction grating (and fiber tilt angle) is designed in such a way that the wavelength band around λ_1 is coupled in the forward direction, while the wavelength band around λ_2 is coupled in the opposite direction. This way, at the same time a duplexing operation is achieved, as both wavelength bands are spatially separated on the photonic integrated circuit [9]. The corresponding Bragg vector diagram of the duplexing grating structure is shown in figure 5b. A prototype duplexer was realized in the diffraction grating configuration of figure 2a, with a grating period of 520nm, a grating etch depth of 70nm, a grating duty cycle of 40% and 20 grating periods long. In the experiment index matching fluid was applied between the optical fiber (tilted 20 degrees off vertical) and the SOI grating. About -6dB coupling efficiency is obtained both for the 1310nm upstream and 1520nm downstream wavelength band. The same approaches for increasing the fiber coupling efficiency as in the case of a single wavelength band diffraction grating can be applied to the duplexing grating structure. For example, simulations show that using a raised grating structure (see figure 2b) for realizing a grating duplexer, a coupling efficiency of -1.9dB can be obtained for the case of 1300nm/1550nm wavelength bands, with a 1dB optical bandwidth of 50nm and 60nm respectively. In figure 5c, the grating duplexer is implemented in an SOI Fiber-to-the-Home transceiver circuit, which duplexes the 1310nm upstream wavelength and the 1490nm/1550nm downstream wavelength band. Both downstream wavelengths are further demultiplexed using a planar concave grating, which at the same time further reduces the crosstalk of the upstream wavelength channel into the downstream wavelength path [10].

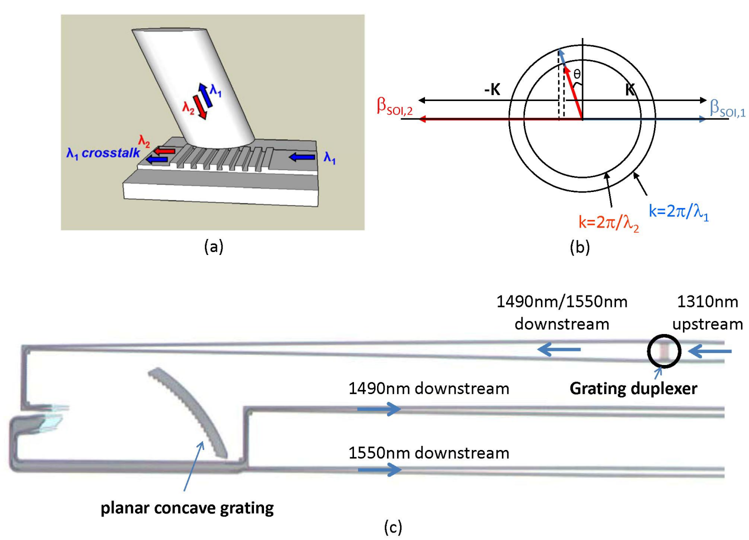

Fig. 5. Grating duplexer structure to couple two wavelength bands to the SOI photonic integrated circuit

4. TWO-DIMENSIONAL GRATING COUPLERS

While one-dimensional diffraction gratings provide an elegant way of interfacing a high refractive index contrast waveguide circuit and a single mode optical fiber, these grating structures are highly polarization-dependent. In order to realize a polarization independent photonic integrated circuit, the concept of a two-dimensional grating structure was developed. This approach is shown in figure 6, which clarifies the operation principle of the device [11].

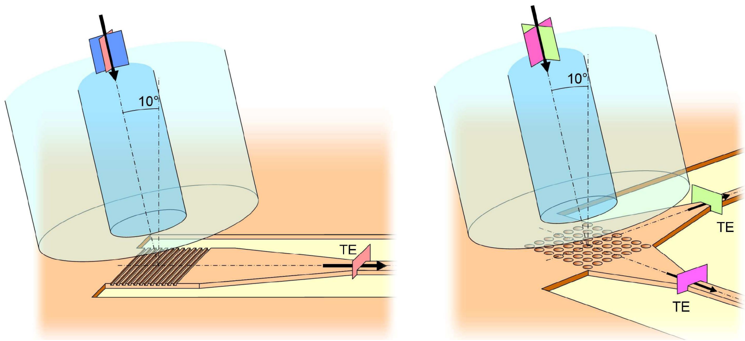

Fig. 6. Operation principle of a two-dimensional diffraction grating.

The two-dimensional grating can be considered as the superposition of two one-dimensional grating structures, which allow coupling both orthogonal polarization states in the optical fiber, towards *identical* transverse electric polarized modes in (nearly) orthogonal waveguides. In this case the optical fiber is tilted along the bisection line of the two-dimensional grating. By duplicating the photonic integrated circuit for each branch of the two-dimensional grating coupler and combining the output(s) of the photonic integrated circuits (if any) to an identical two-dimensional grating coupler, in principle polarization independent operation can be obtained (referred to as a polarization diversity approach) as shown in figure 7 (top illustration). This requires however an exact replication of the photonic integrated circuit in both arms of the polarization diversity arm, which puts stringent requirements on the deep UV lithography. In some cases this problem can be avoided, by using the same integrated circuit for both branches of the polarization diversity configuration, as shown in the bottom illustration in figure 7. In this case the polarization dependent loss is limited by the performance of the two-dimensional grating couplers.

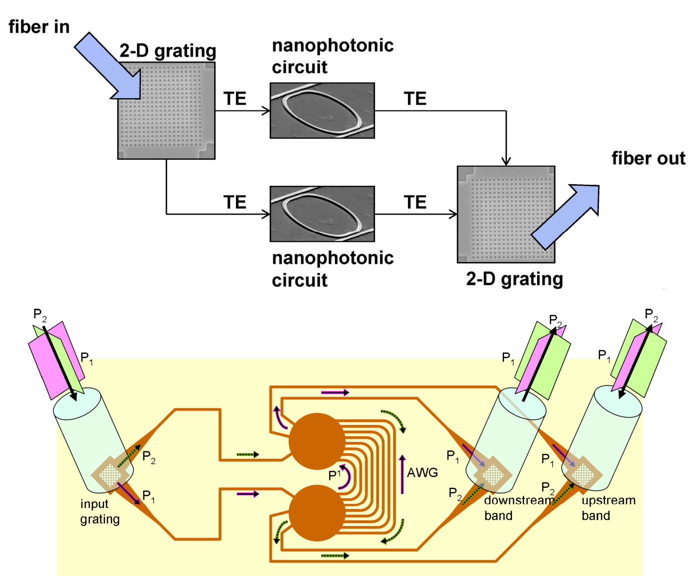

Fig. 7. Polarization diversity based on a two-dimensional diffraction grating: operation principle (top) and practical implementation which avoids the doubling of required integrated components (bottom)

Experimentally, a strong wavelength dependence of the polarization dependent loss is observed as shown in figure 8. While PDL values down to 0.2dB can be obtained, the polarization dependent loss rises significantly moving away from the central wavelength. However, the PDL remains lower than 1dB over a 40nm wavelength range. This wavelength dependence of the PDL is related to the tilting of the optical fiber.

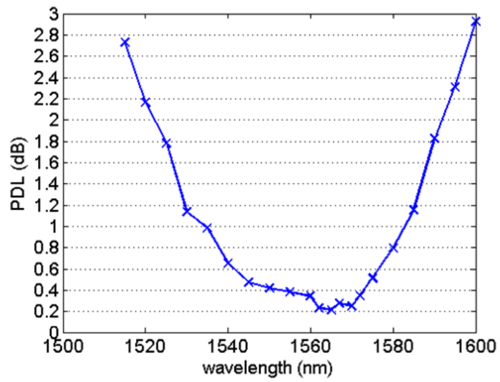

Fig. 8. Wavelength dependence of the polarization dependent loss of two-dimensional grating couplers

Besides using the standard square lattice two-dimensional grating structures requiring long spot size converters, also a focusing two-dimensional grating structure can be designed in order to avoid the lengthy adiabatic taper structures. These gratings can be designed by overlaying two one-dimensional curved gratings and defining a scatter center at the various intersections. The design method and an experimentally realized structure are illustrated in figure 9. The efficiency and polarization dependent loss is comparable to standard square lattice two-dimensional gratings, while having a much smaller footprint [12].

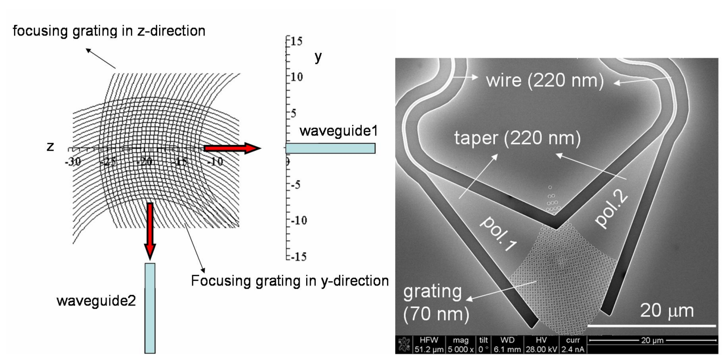

Fig. 9. Design and implementation of a focusing two-dimensional diffraction grating

Currently the optimization of two-dimensional duplexing grating structures, as the one schematically illustrated in figure 10, is on the way. Prototype devices based on the grating layout shown in figure 2a, show a coupling efficiency of -7dB both for the 1300nm wavelength band and the 1550nm wavelength band. The polarization dependent loss still has to be assessed in detail and will be discussed at the conference.

5. FIBER PROBES

An important step toward wide scale applications of photonic integrated circuits is the ability to test the operation and performance of circuit parts and components on a wafer scale. In microelectronics manufacturing, probes exist in the form of metal tips and are widely used for wafer-scale, non-destructive, and parametric testing. Using diffractive grating

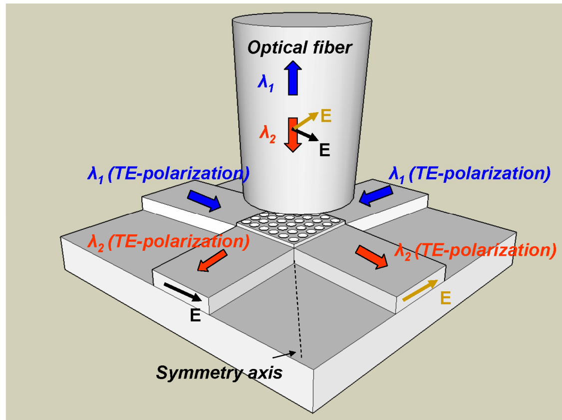

Fig. 10. Two-dimensional grating duplexer layout for polarization independent duplexing of two wavelength bands

structures, an equivalent optical fiber probe can be realized. By realizing the diffraction grating on the (angled) facet of an optical fiber, no coupling features are required on the SOI waveguide circuit to interface with the fiber probe, thereby allowing the testing of individual integrated photonic components in a PIC [13]. A prototype fiber probe was realized by defining a uniform metallic periodic structure on the core of a single mode fiber, by means of imprint technology as shown in figure 11. First, the fiber with UV-curable resist on the facet is aligned over a specially prepared mold carrying the 10 µm by 10µm gold grating pattern in the mold trenches. The mold was obtained by starting off from an SOI sample containing silicon gratings of period 630 nm and an etch depth of 220 nm. This surface was treated with an antistiction coating. Then, gold was evaporated onto the mold. Finally, the gold on top of the mold grating lines was selectively removed by microcontact printing on another substrate. In this way, the original SOI mold becomes a carrier of the gold grating pattern by leaving the gold only in the grating trenches. After attachment of the fiber to the mold, the cavities are filled and the resist is UV cured (step 2). Finally, the mold is released. The metal grating is now attached to the fiber.

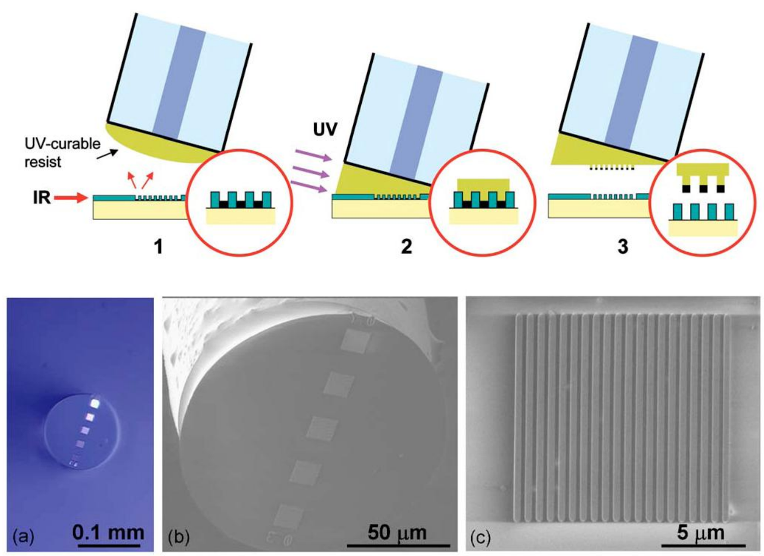

Fig. 11. Fabrication flow (a) and experimental realization (b) of optical fiber probes

Two gold grating fiber probes were fabricated both consisting of a gold grating of thickness 20nm. Both probes were brought into contact with a straight 220nm by 3µm SOI waveguide. 15% coupling efficiency and a 1dB bandwidth of 38nm was demonstrated in this way for transverse electric polarized light, which is sufficient for testing purposes.

6. CONCLUSIONS

Diffractive grating structures provide an elegant way of interfacing a high refractive index contrast single mode fiber and a nanophotonic integrated circuit. Polarization independent, large optical bandwidth, high efficiency coupling can be obtained. Even duplexing of two wavelength bands can be realized using the same type of structure. As diffractive grating structures allow accessing a photonic integrated circuit, it paves the way to wafer scale testing of PICs. In this paper the focus was on the interfacing of a single mode fiber and a photonic integrated circuit. It is however possible to also interface hybrid integrated opto-electronic components such as flip-chipped photodetectors and VCSELs with the photonic integrated circuit, allowing the realization of complex active/passive photonic integrated circuits.

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