

# High-Efficiency Fiber-to-Chip Grating Couplers realized using An Advanced CMOS-Compatible Silicon-On-Insulator Platform

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**Abstract:** A new generation of Silicon-on-Insulator fiber-to-chip grating couplers which use a silicon overlay to enhance the directionality and thereby the coupling efficiency is presented. Devices are realized on a 200mm wafer in a CMOS pilot line. The fabricated fiber couplers show a coupling efficiency of  $-1.6$  dB and a 3 dB bandwidth of 80 nm.

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## 1. Introduction

In the last decade much research has focused on silicon photonic integrated circuits, due to the scaling in size that can be accomplished because of the high refractive index contrast available on the SOI material platform. However, the scaling of the device cross-section complicates the interfacing with a single mode optical fiber. Several schemes have been proposed to tackle this problem. We focused particularly on fiber-to-chip coupling by means of subwavelength structured surfaces such as line gratings or photonic crystals. With these grating couplers one can couple out-of-plane and thus test photonic circuits on a wafer-scale without the need of any post-processing or cleaving. Furthermore because of a relaxed 1dB alignment sensitivity of  $2\mu\text{m}$ , it is even possible to align several optical fibers at the same time by using fiber arrays for wafer-scale testing or packaging. Despite the fact that these grating couplers are a very good candidate for fiber interfacing for the low cost and high volume oriented silicon photonics framework, they suffer from relatively high coupling loss, making them only useful for research purposes or specific applications with a relaxed power budget.

In 2002 we reported an SOI grating coupler with a fiber coupling efficiency of  $-7\text{dB}$  [1]. Since then, a lot of attempts were made to improve the coupling efficiency significantly. In general there are three factors that contribute to the poor coupling efficiency of standard grating couplers. Most of the light 35% – 45% is lost because of diffraction towards the substrate and around 20% is lost because of poor mode-matching to the Gaussian shaped mode of the fiber. For perfectly vertical coupling another 30% is reflected back into the waveguide due to second order Bragg diffraction. This last issue can be easily solved by coupling under a small angle which breaks the symmetry and eliminates the reflection [2]. An alternative method is to etch a deep slit in front of the grating which acts together with the grating as a Fabry-Perot cavity [3]. By chirping the grating, back reflections [4] and losses due to mode-mismatch [5] can be minimized. Most attempts to increase the directionality of the grating all involve substrate engineering [6]. Other approaches are either based on amorphous silicon, which limits the thermal budget [7], or require a lot of post-processing [8]. Alternatively, one can use exotic gratings with for example slanted facets, in analogy to a blazed grating, to enhance the coupling to the first diffraction order in the superstrate [9]. In 2006 however, we proposed a rather simple and elegant way to adapt the grating and increase the coupling efficiency drastically, i.e. by defining a silicon overlay prior to etching the grating [10]. Early attempts which involved epitaxial silicon growth were promising and showed efficiencies up to  $-2.6\text{dB}$  [11]. In this paper we demonstrate high efficiency grating couplers, fabricated in a CMOS pilot line, with  $-1.6\text{dB}$  coupling efficiency, approaching the coupling efficiencies required in practical applications.

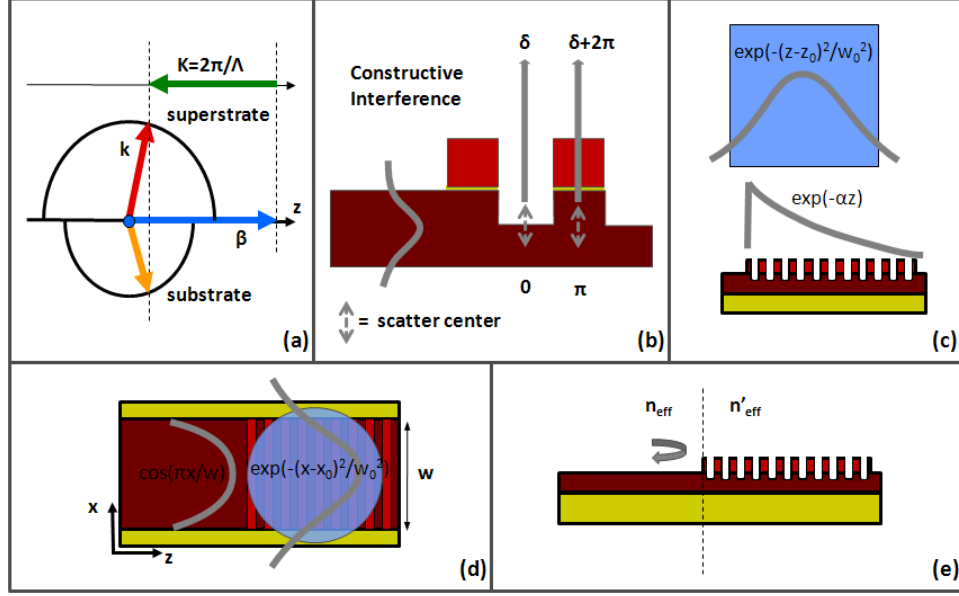


Fig. 1. Schematic illustrations of fiber-to-chip high index contrast grating coupler optimization factors: the Bragg condition (a), upwards directionality (b), 2D fiber mode-matching in  $z$ - and  $x$ -direction (c,d) and mode-matching between the waveguide and Bloch mode of the grating (e).

## 2. Fiber Coupler Grating Design

For designing a fiber-to-chip grating coupler, which is inherently highly efficient, several design issues have to be taken into account. These are summarized in Figure 1. The first order diffraction of a grating is described by the Bragg condition  $\beta - K = k_z$  where the propagation constant of the guided mode  $\beta = \frac{2\pi}{\lambda} n_{eff}$ ,  $K = \frac{2\pi}{\Lambda}$  and the projected wavevector of the incident mode  $k_z = \frac{2\pi}{\lambda} \sin \theta$  with  $\lambda$  the wavelength of the light,  $\Lambda$  the period of the grating and  $\theta$  the angle of the fiber with respect to the surface normal of the grating. In order to avoid a high second order reflection, it is convenient to couple in under a positive fiber angle as shown in Figure 1(a). In general the effective refractive index  $n_{eff}$  of the grating is a function of the grating parameters shown in Figure 2(a). However, since for a given grating period and given fiber angle it is almost always possible to find a wavelength at which the bragg condition is fulfilled, this dependency will have a minor influence on the maximal coupling efficiency of the grating coupler but rather on the central wavelength of the coupling spectrum. In the rest of the analysis we will assume that the Bragg condition is satisfied and that the fiber coupling angle  $\theta$  is close to zero.

The physical principle behind a highly directional grating as shown in Figure 1(b) 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  $\pi$  phase shift with respect to each other for a perfect vertically coupling grating), constructive interference towards the superstrate (and hence the optical fiber) can be achieved by realizing an additional  $\pi$  phase shift during the propagation towards 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  $o$  (see Figure 2). 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, shown in Figure 1(c). This mode-matching requirement is a function of the same three parameters  $h$ ,  $e$  and  $o$  as the high directionality condition. Three different classes of grating cases shown in Figure 2 can be considered which can be favorable, depending on the considered photonics platform, robustness and cost considerations.

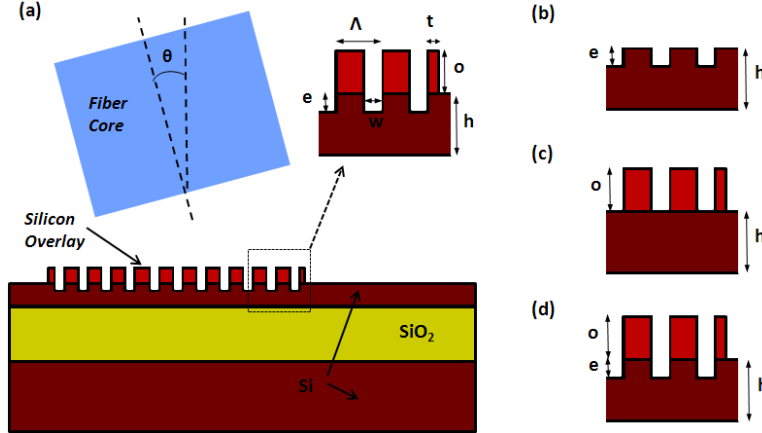


Fig. 2. Parameterized highly directional grating couplers: the general case (a), without silicon overlay (b), with silicon overlay but no waveguide etch (c) and both silicon overlay and waveguide etch (d).

The first case 2(b) is a grating without silicon overlay where high directionality and an optimal grating strength is only achieved for a certain waveguide thickness  $h$  and etch depth  $e$ . In [12] this grating type is optimized and a coupling efficiency of  $-1.2\text{dB}$  is achieved for a waveguide thickness  $h$  of  $340\text{nm}$  and a deep waveguide etch depth  $e$  of  $200\text{nm}$ . Important drawbacks are the fixed waveguide thickness which is multimode and the deep waveguide etch depth which introduces a large mode mismatch between the waveguide mode and the Bloch mode of the grating resulting in high back reflections (see Figure 1(e)). The last issue is improved by apodizing the grating, leading to reduced reflections and a better mode matching with the Gaussian fiber mode. However, an apodized grating requires feature sizes which are beyond the limit of current  $193\text{nm}$  DUV lithography.

For case 2(c), no waveguide etch  $e$  is required. This kind of grating coupler has been theoretically reported in [13], where a transferred silicon nanomembrane is proposed in order to fabricate the grating. For a waveguide thickness  $h$  of  $220\text{nm}$  and a silicon overlay thickness  $o$  of  $240\text{nm}$  the simulated efficiency was  $64\%$ . We optimized this grating type and simulated for a uniform grating with  $h = 150\text{nm}$  and  $o = 220\text{nm}$  around  $80\%$  coupling efficiency, which is the theoretical upper limit because of the mode mismatch between the exponential shaped electrical field profile of the uniform grating and the gaussian shaped mode of the optical fiber. Unfortunately, a waveguide thickness of  $h = 150\text{nm}$  leads to a lower confinement of the TE optical mode, and does not support any TM polarized waveguide modes. We also like to point out that the coupling strength of a grating with no waveguide etch is solely dependent on the silicon overlay and thus on the evanescent field of the waveguide mode. Because this evanescent field is different for orthogonal polarized waveguide modes, it is unlikely that there exists a grating which is highly efficient for both polarizations. Despite these drawbacks, this grating coupler type could be an ideal candidate for using in a single-polarization low-cost photonics platform. This grating can be made very robust and with only one combined grating/waveguide

etch step by using an oxide etch stop layer between the waveguide and silicon overlay, thereby following a similar fabrication process as will be described in the fabrication section.

The most general fiber coupler grating using a silicon overlay is case 2(d) where both a silicon overlay  $o$  and waveguide etch  $e$  is used to define the grating. This gives us the freedom to choose an appropriate waveguide thickness  $h$  of for example 220 nm. This high efficiency grating coupler type is theoretically described in [10] and shows around 80% of coupling efficiency according to simulations. Although it requires more process steps than the previous cases, it is compatible with any high index contrast photonic platform. Moreover, the introduced additional thickness levels could be used to optimize other integrated photonic devices. An optimization issue that is unrelated to the previous discussion is the mode-matching between the Gaussian fiber mode and the waveguide mode in the x-direction as is shown in Figure 1 (d). For a 220 nm thick waveguide, the optimal waveguide width  $w$  is 15  $\mu\text{m}$ . Since the taper length scales quadratic with the waveguide width, a long taper section ( $\approx 500 \mu\text{m}$ ) would be needed to adiabatically transform the broad waveguide of the grating into a single-mode optical waveguide. This can be easily solved by curving the grating as is demonstrated in [14] or using a focusing taper [15], without decreasing the grating coupling efficiency.

### 3. Fabrication

We developed an advanced Silicon-on-Insulator process flow which is capable of realizing the most general case in Figure 2(d) of the high efficiency grating couplers. The complete fabrication process is done in the 200 mm *imec* CMOS pilot line with 193 nm DUV lithography. First a very thin silicon oxide layer is deposited on top of a 200 mm SOI wafer with a buried oxide layer thickness of 2  $\mu\text{m}$  and a crystalline silicon layer thickness of 220 nm. Simulations show that the thickness of the buried oxide layer is of no importance for the grating directionality, since the grating intrinsically is very directional and does not have to rely on the oxide/silicon interface reflection to achieve constructive interference towards the optical fiber. In a second step an amorphous silicon layer of 160 nm is deposited and a deep etch is performed through the amorphous silicon and oxide layer reaching 70 nm into the crystalline silicon layer. This is used to define the slits of the high efficiency grating couplers. Next, the amorphous silicon is removed where necessary and the deposited oxide layer in the first step will now act as an etch stop layer in order to not affect the underlying crystalline silicon. The width of the first tooth will not affect the grating coupling efficiency if it is narrower than the subsequent teeth. By contrast, larger first tooth widths introduce a rapid decrease of the coupling efficiency. Anticipating possible mask misalignment between the silicon overlay and the grating etch step is done by deliberately designing the first tooth smaller. This can be clearly seen in Figure 3 where a side view image of the fabricated silicon overlay grating is shown. In the final step the strip waveguides are defined in the crystalline silicon layer. The measured propagation loss for a straight single-mode waveguide of 450 nm was 1.8 dB/cm, demonstrating the high process quality of this advanced SOI fabrication process.

### 4. Experimental Results

The measurement results are shown in Figure 4. All measurements were performed with a single-mode fiber tilted under an angle of 13 degrees relative to the surface normal of the grating. Index matching fluid was applied between the grating and fiber facet to reduce Fresnel reflections. TE polarized light is used in all experiments, since the gratings behave very polarization dependent. Figure 4(a) shows the central wavelength of the fiber coupling spectrum as a function of the grating period and this for several duty cycles. The central wavelength scales almost linearly with the grating period because the effective refractive index of the grating is only weakly dependent upon the wavelength. In Figure 4(b), the coupling efficiency for diffe-

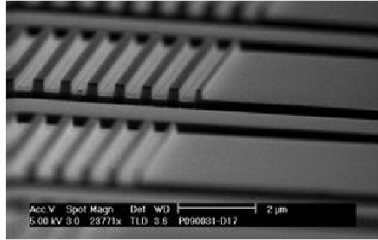


Fig. 3. Bird's eye view of a silicon overlay grating fiber coupler.

rent grating periods is plotted versus the duty cycle. It seems that a duty cycle of 35% (refers to the unetched silicon part) is optimal and we measured a maximum efficiency of  $-1.6$  dB with a 3 dB bandwidth of 80 nm for a grating period of 690 nm and central wavelength of 1530 nm. This is the highest fiber coupling efficiency reported to date for CMOS-compatible fiber-to-chip grating couplers.

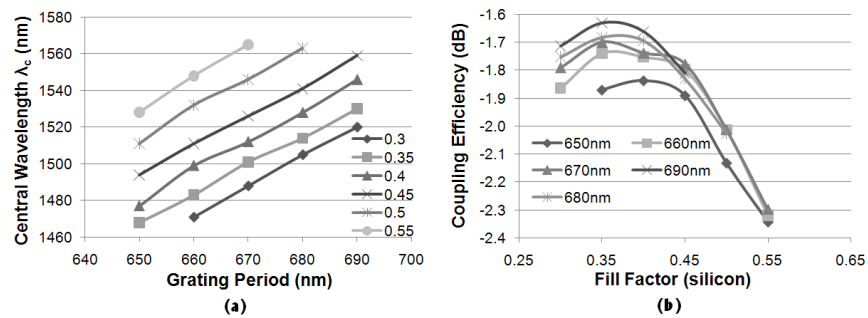


Fig. 4. Measurement results of a sweep of 1D fiber couplers (a-Si overlay) for different duty cycles (a) and different grating periods (b).

## 5. Conclusion

Different types of high efficiency grating couplers which are inherently highly directional are discussed. The most general case of a grating coupler with silicon overlay and etch into the optical waveguide is fabricated using 193 nm DUV lithography. We have shown experimentally a coupling efficiency of  $-1.6$  dB which is the highest fiber coupling efficiency for grating couplers fabricated in a CMOS pilot line. The optimal duty cycle of the grating is found to be 35%. A silicon overlay could also be beneficial for more advanced grating couplers which incorporate polarization diversity and wavelength demultiplexing [16]. Besides the grating couplers, the silicon overlay can be used in other components on the SOI chip as an extra degree of design freedom.

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