Cost-effective CMOS-compatible grating couplers with backside metal mirror and 69% coupling efficiency

Wissem Sfar Zaoui,1,* María Félix Rosa,1 Wolfgang Vogel,1 Manfred Berroth,1 Jörg Butschke,2 and Florian Letzkus2

1Institute of Electrical and Optical Communications Engineering, University of Stuttgart, Pfaffenwaldring 47, 70569 Stuttgart, Germany
2Institut für Mikroelektronik Stuttgart, Allmandring 30a, 70569 Stuttgart, Germany
*wissem.sfarzaoui@int.uni-stuttgart.de

Abstract: A highly efficient grating structure for the coupling between standard optical fibers and single-mode waveguides in the silicon-on-insulator platform realized in a CMOS fabrication process is presented. The cost-effective method introduces a backside metal mirror to the grating coupler without need of an extensive wafer-to-wafer bonding. A coupling efficiency of −1.6 dB (around 69%) near the telecommunication wavelength 1550 nm and a large 1dB-bandwidth of 48 nm are achieved.

References and links


1. Introduction

Due to the large dimension mismatch between the standard single mode optical fiber core and integrated waveguides in the promising silicon-on-insulator (SOI) platform, high coupling losses exist between silicon photonic integrated circuits (SiPIC) and the outside world.
ensure the single mode condition, the integrated SOI waveguides have dimensions as small as 0.5 \( \mu m \) x 0.25 \( \mu m \), whereas the core of a single mode fiber (SMF) has a diameter around 10 \( \mu m \). Meanwhile, the SOI platform has become unforfeitable for designing optoelectronic devices owing to the high integration possibility driven by the large refractive index difference between silicon (Si) and silicon dioxide (SiO\(_2\)) and the complementary metal-oxide-semiconductor (CMOS) compatibility, offering compactness and cost effectiveness in the puzzle elements of optical communication networks for bit rates of 100 Gbit/s and beyond. The connection of optical integrated transmitters and receivers to the fiber backbone is a non-trivial task since coupling to the PICs requires large alignment tolerance, high bandwidth and especially high efficiency.

An elegant way to ensure a good broadband coupling efficiency between SMFs and SiPICs has been presented the last years using Bragg structures called grating couplers [1]. In addition to an acceptable alignment tolerance, these elements allow a simple vertical on-wafer characterization instead of complicated butt-coupling and additional cleaving steps. They can be realized as one or two-dimensional [1,2] structures and can serve to couple one or both orthogonal polarization states, acting as polarization beam splitters [2,3]. The first fabricated standard grating couplers had a coupling efficiency of around \(-5\) dB [4]. By a careful design this value can be theoretically furthermore enhanced to better than \(-1\) dB.

Efficient coupling is achieved by matching the diffracted field to the Gaussian mode profile of the SMF and increasing the directionality, i.e. the ratio of the diffracted optical power from the fiber toward the integrated waveguide, or vice versa, to the total diffracted power. As the first issue is settled by an adequate design of the gratings period, fill factor, etch depth and incident angle, the second challenge requires the use of a backside mirror at an adequate distance to redirect constructively the diffracted power toward the substrate back to the Si waveguide. Despite material thickness engineering, this loss can exceed 30\% and represents the main reason for the degraded efficiency in structures without backside mirrors. For this purpose two solutions have been utilized: a distributed Bragg reflector (DBR) [5] and a metal layer as a perfect mirror [6,7]. A third solution to enhance the coupling efficiency has also been recently presented and proposes the use of a Si overlay that makes the structure “intrinsically” directional without the need of reflecting back downward optical power [8]. All three solutions assured a high coupling efficiency of \(-1.6\) dB near the telecommunication wavelength 1550 nm, however with certain technological drawbacks. As the latter solution needs the introduction of an additional amorphous Si layer, the former method with the DBR necessitates at least two sequences, where each sequence is composed of Si and SiO\(_2\) layers with exact dimensions of a quarter wavelength each. Moreover, the solution that introduces a gold metal mirror requires many extensive steps in a CMOS non-compatible process with a wafer-to-wafer bonding technique.

In this work we present highly efficient grating couplers with a backside aluminum (Al) mirror to enhance the directionality of the structure. The fabrication has been realized in a CMOS line, without the need of wafer-to-wafer bonding procedures, thus, simplifying the realization of cost-effective interfaces between SMFs and SiPICs.

### 2. Grating couplers design

To design a coupler with periodic gratings that serve to couple the light from a fiber to a waveguide or vice versa, the Bragg condition

\[
 k_{in} \sin \alpha + m \frac{2\pi}{\Lambda} = \beta
\]

has to be first fulfilled. Here, \( k_{in} = \frac{2\pi n_{top}}{\lambda_0} \) is the incident wave number with the refractive index of the top cladding layer \( n_{top} \) and the free space wavelength \( \lambda_0 \), \( \alpha \) is the fiber off-vertical tilt angle, \( m \) is the diffraction order, \( \Lambda \) is the grating period, and \( \beta = \frac{2\pi n_{eff}}{\lambda_0} \) is the...
propagation constant of the optical mode in the gratings with the effective refractive index \( n_{\text{eff}} \). Commonly, these different parameters are optimized to have a maximum coupling efficiency only for the diffraction mode \( m = 1 \). This has been realized by two-dimensional finite-difference time-domain (FDTD) simulations using the commercial software RSoft FullWAVE [9] after fixing some structure dimensions and material parameters. Using an SOI-platform with a Si-layer thickness of 250 nm, the gratings are designed to be etched 70 nm in this layer with a fill factor \( FF = 0.5 \). After optimizing the grating period, the tilt angle, and the lateral fiber position along the \( z \)-direction to achieve a maximum mode matching at a wavelength of 1550 nm for the transversal electric (TE) polarization state, the thickness of the buried oxide (BOX) has been investigated since it has to produce a constructive interference between the diffracted field toward the film layer and the field that is reflected at the bottom metal mirror to increase the directionality of the grating coupler, and hence to guarantee a maximum transmission from the fiber to the integrated waveguide. Here, the grating period and the tilt angle are chosen as \( \Lambda = 600 \text{ nm} \) and \( \alpha = 9^\circ \), respectively. Other \( \Lambda/\alpha \)-combinations are also possible to get a comparable high transmission when the fiber position is appropriately defined. Figure 1(a) illustrates the proposed structure with the BOX-thickness \( d_{\text{BOX}} \) and the Al mirror underneath [10].

The simulated coupling efficiency of the proposed structure versus the BOX-thickness in Fig. 1(b) shows that constructive interference occurs at \( d_{\text{BOX}} = 2.95 \text{ \( \mu \text{m} \)} \) where a maximum of \(-0.76 \text{ dB}\) can be achieved. Since the behavior is periodic with a difference of a half wavelength between two consecutive peaks, smaller BOX-thicknesses can also be used to obtain the same result. For the fabrication process a standard SOI-wafer with a 3 \( \mu \text{m} \) SiO\(_2\) substrate and a 250 nm thick top Si-layer is used [11]. This has the advantage to simplify the fabrication process and minimize the costs since the metal mirror can be directly placed underneath the BOX after etching a membrane window without additional technological steps to adjust \( d_{\text{BOX}} \). At 3 \( \mu \text{m} \) the coupling efficiency still reaches a high value of \(-0.82 \text{ dB}\).

Figure 1(c) shows the simulated electric field distribution of the structure with the above mentioned parameters at a wavelength of 1550 nm. In this simulation a 10 \( \mu \text{m} \) wide Gaussian beam is launched onto the coupler and diffracted at the gratings to the waveguide and toward the substrate. The latter part of light is then reflected back at the metal mirror and is driven again to the waveguide, leading to a high coupling efficiency. To investigate the spectral
properties of the presented grating coupler in comparison to a similar structure without the metal mirror, a second simulation has been carried out at wavelengths between 1500 nm and 1600 nm. Monitors are moreover placed appropriately to calculate the reflected power above the gratings and the diffracted part toward the Si substrate. The results are illustrated in Fig. 2.

The normalized transmission spectrum of the grating coupler without the metal mirror in Fig. 2(a) shows that a coupling efficiency of $-2.2$ dB at 1550 nm can be achieved. Indeed, the Si-layer/BOX interface represents a mirror due to the large refractive index difference between Si and SiO$_2$, but only a fraction of $R = (n_{Si} - n_{SiO2})^2 / (n_{Si} + n_{SiO2})^2 = 17\%$ of the diffracted power can be reflected back and contributes to the coupling efficiency. Here, the refractive index of Si and SiO$_2$ at a wavelength of 1550 nm are $n_{Si} = 3.474$ and $n_{SiO2} = 1.444$, respectively. Hence, a considerable part of the power around $-5$ dB (more than 30\%) is refracted to the bottom Si substrate and is lost. The reflected part of power at the gratings is relatively low and approaches $-12$ dB (around 6\%) at the target wavelength. Figure 2(b) shows an appreciable improvement of around 1.4 dB in the coupling efficiency, which increases to $-0.82$ dB, as discussed above. Since the diffracted power toward the substrate is reflected at the perfect metal mirror, an important part is redirected to the TE-output and enhances the efficiency of the grating coupler. Besides, a 1dB-bandwidth amelioration from 45 nm to 56 nm and a 3dB-bandwidth from 78 nm to 91 nm are theoretically achievable.

3. Fabrication and measurement

The starting point is a standard SOITEC wafer with a 3 $\mu$m SiO$_2$ substrate and a 250 nm thick top Si-layer. The designed structures are fabricated according to an SOI wafer flow concept using standard technological processes [12]. In a first step the gratings are defined by electron beam lithography and the pattern transfer into the top Si-layer is realized by means of dry etching until an etch depth of 70 nm. In a second lithography step the definition of the waveguide structures is performed and the top Si-layer is dry etched until the BOX. The following protection layer deposition is of main importance since it regulates the stress of the whole system and prevents the thin Si layer to break. This is done by a SiO$_2$ passivation, which serves also as a cladding and ensures a symmetric environment to the gratings and waveguides. Finally, the mirror windows are defined on the wafer backside and are wet etched until the BOX, so that an appropriate metal deposition (e.g. aluminum) can be achieved in the membrane cavity. The mirror windows can also be realized in a similar way using a dry etching process. This cost-effective procedure represents a major simplification to the CMOS non-compatible process introduced in [6] that uses an extensive wafer-to-wafer
bonding process in addition to a gold layer as metal mirror of the grating coupler. Thereby, the gratings are structured on the SOI-wafer; afterwards an adequate polymer and a gold layer are deposited, and then the thick Si substrate is removed, so that the BOX becomes the top cladding. Finally, the wafer is bonded with another host wafer, and hence the fabrication process cannot be transferred to a standard CMOS line.

Figure 3(a) shows a picture of a fabricated structure with two identical grating couplers serving as input and output optical power interfaces, linked by a 1 mm long and 10 µm wide waveguide, and having a metal mirror below each of them. The inset is a zoom-in of the gratings etched in the Si-layer. Figure 3(b) depicts a front and a back side view of the chip where the mirror window is clearly seen.

To determine the coupling efficiency of the grating coupler in the conventional optical telecommunication band, a measurement setup composed of a tunable laser source, a polarization controller and an optical power meter have been used. Piezoelectric elements have also been utilized to exactly adjust the fibers on the grating couplers. The coupling efficiency in dB is then calculated as

\[ \eta_{dB} = -\frac{1}{2} \left( P_{in,\text{dBm}} - P_{out,\text{dBm}} - a_S - a_W \cdot L \right) \]  

where \( P_{in,\text{dBm}} \) is the laser optical power, \( P_{out,\text{dBm}} \) is the measured output power, \( a_S \) is the setup loss including connectors and polarization controller loss, \( a_W \) is the waveguide loss per unit length and \( L \) is the waveguide length. For simplicity, waveguides with a width of 10 µm have been designed to connect the grating couplers; therefore the waveguide loss is very small and can be neglected (=0.05 dB/mm). When designing the structures using single mode waveguides having widths in the order of 500 nm, an adequate tapering and larger additional waveguide losses, especially caused by the sidewall roughness, have to be taken into consideration. In order to prevent Fresnel reflections between optical fibers and grating couplers a standard index matching liquid with a refractive index of around 1.45 at 1550 nm has been used [13].

Figure 4 illustrates the coupling efficiency of three grating couplers with different periods from 595 nm to 605 nm at a fiber tilt angle of 8° over the wavelength. The zoom-in of the figure shows that a maximum coupling efficiency of −1.63 dB (around 69%) at a wavelength of 1539 nm is achieved using a structure with \( \Lambda = 600 \) nm. The discrepancy to the simulated results can be explained by the fluctuation of the BOX-thickness over the wafer and some deviation from the designed target values. Nevertheless, the obtained coupling efficiency using the presented cost-effective CMOS-compatible technique is state-of-the-art. The 1dB-bandwidth is measured to be 48 nm, whereas the 3dB-bandwidth is around 78 nm.
To emphasize the coupling efficiency enhancement of the introduced Al mirror on the coupler backside, a similar structure with $\Lambda = 600$ nm has been fabricated on the same wafer without mirror. It can be seen in Fig. 5 that an amelioration of 1.6 dB can be achieved due to the increase of the directivity, and hence a better transmission, as predicted in the simulations.

**4. Conclusion**

We have presented in this work a grating coupler that allows high coupling efficiency from standard single mode optical fibers to photonic integrated circuits realized by a simple and cost-effective CMOS compatible technological method. We have designed, fabricated and measured a structure with an efficiency of $-1.6$ dB at a wavelength of 1539 nm and a 1dB-bandwidth of 48 nm for TE polarization using a standard SOITEC wafer with 3 $\mu$m BOX-thickness. This method can also be used to enhance the capability of other types of couplers as the two-dimensional structures and the polarization splitters when designing the mirror adequately.

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