# Focusing polarization diversity gratings for Silicon-on-Insulator integrated circuits

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*Abstract*—**We present experimental results for focusing grating couplers for coupling between optical fiber and nanophotonic Silicon-on-Insulator waveguides in polarization diversity configuration. The footprint is reduced by a factor of 8 compared to standard grating couplers.**

## I. Introduction

Using high index contrast is the key to miniaturization and high-density integration of optical components on a single chip. Silicon-on-Insulator is evolving as a promising platform in this respect [1, 2]. For the fabrication, high-volume and mature processes from CMOS industry can be used [3].

An important issue remains the interfacing of the optical chip with the outside world (i.e. optical fiber). As waveguides and optical components tend to become smaller, the mismatch between the optical fiber mode and the mode size on the chip becomes larger, resulting in high coupling losses. Additionally, there is a polarization problem. Light from the fiber has an unknown polarization which also changes over time, while the devices on the chip are often very polarization sensitive (especially when using high index contrast). Polarization diversity solves this problem in an elegant way. Some implementations, using on-chip polarization splitters and rotators, have been demonstrated [4, 5]. However, these additional components are often long and decrease the integration density.

We use compact diffraction gratings for (near) vertical coupling between fiber and chip. While 1D-gratings [6] are very polarization selective, a 2D-grating in combination with two orthogonal waveguides can be used both for fiber coupling and integrated polarization diversity [7], without on-chip polarization splitters and rotators. However, the total length of the coupling structure is determined by an adiabatic transition (> 150 μm) from a 12 μm wide waveguide (i.e. the size of the grating) to a single-mode photonic wire.

In this paper, we will circumvent this adiabatic transition by using focusing grating couplers, which results in an 8-fold length reduction of the coupling structure without performance penalty. Thus, the integration density is substantially increased. The fiber-to-fiber Polarization Dependent Loss (PDL) is 0.5 dB.

## II. Design

### A. Principle

A 2D-grating can be seen as a superposition of two orthogonal (polarization selective, e.g. working for TE-polarization) 1D-gratings. Each orthogonal polarization from the input light couples to its own (orthogonal) waveguide, and in the waveguides the polarization is TE. Both arms then feed an identical polarization sensitive device (working for TE) and are then recombined with another grating coupler.

In analogy with this reasoning, a focusing 2D-grating can be seen as a superposition of two orthogonal focusing 1D-gratings, which we have demonstrated in [8]. The grating lines of a 1D-focusing grating coupler are obtained by [9] :

$$q\lambda_0 = n_{eff}\sqrt{y^2+z^2} - zn_t\cos\theta_c$$

where q is an integer number for each grating line, z the coordinate in the propagation direction, y the coordinate in the lateral direction. The focal point is at the origin, $\theta_c$ is the angle between the fiber and the chip surface, $n_t$ is the refractive index of the environment, $\lambda_0$ the vacuum wavelength and $n_{eff}$ the effective index in the grating area. The right part of this formula is determined by the phase difference between the focusing wave towards the photonic wire and the input wave from the fiber. For vertical coupling (θ=90°), the grating lines are circles with the center as the focal point. For coupling at an angle (e.g. θ=80°) the grating lines are ellipses with one common focal point. The focal distance (determining the minimum q value) is chosen such that a spherical wave diffracting from the aperture matches the lateral dimension of the fiber mode in the center of the grating.

### B. Coupling at an angle

Vertical coupling results in large second order reflections. In order to avoid this, the fiber has to be tilted. For the polarization diversity configuration, the fiber must be tilted along the bisection line of the grating in order to preserve symmetry. This is shown in Figure 1 (right).

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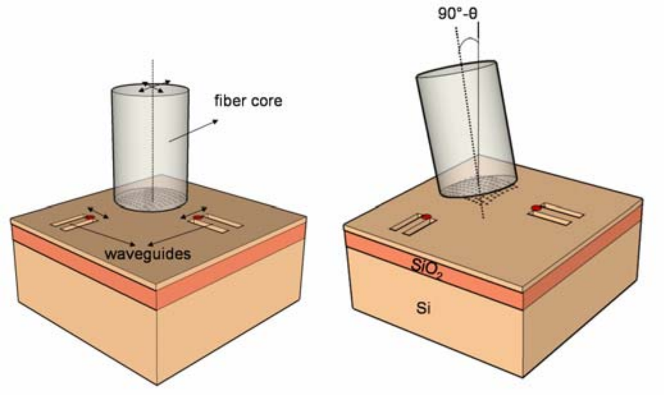


Figure 1. Polarization diversity using focusing grating couplers. (Left) Vertical fiber. (Right) Near vertical fiber in order to avoid second order reflections.

The right part of the grating line equation is changed accordingly and the equation becomes:

$$q\lambda_0 = n_{eff}\sqrt{y^2+z^2} - (y-z)n_t\cos\theta_c\cos\frac{\pi}{4}$$

The 2D-focusing grating is obtained by overlaying two (orthogonal) 1D-gratings, and placing a hole at the intersection of both gratings. This overlay is shown in Figure 2.

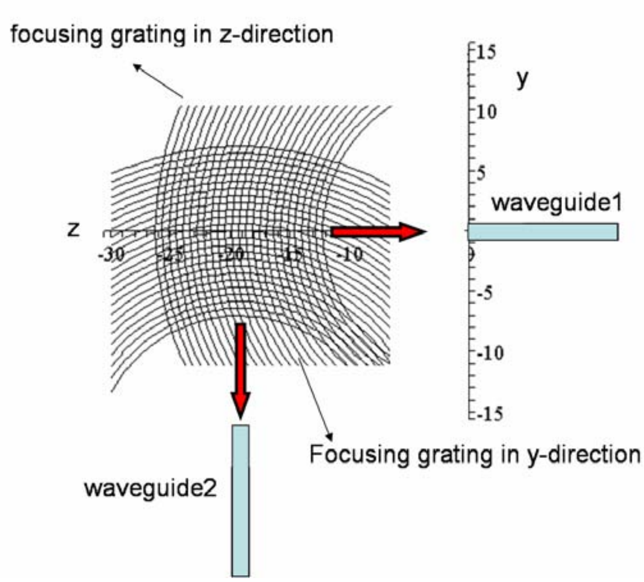


Figure 2. Overlay of two orthogonal 1D-focusing grating couplers.

## III. Fabrication

The layer structure consists of a 220 nm top Silicon layer on a 2 μm oxide layer on a Silicon substrate. Patterns are defined using 193 nm deep UV lithography and dry etching. Two different etch depths are used (70 nm and 220 nm), each requiring a separate patterning step. SEM-pictures of fabricated structures are shown in Figure 3. The grating size is around 20x20 μm.

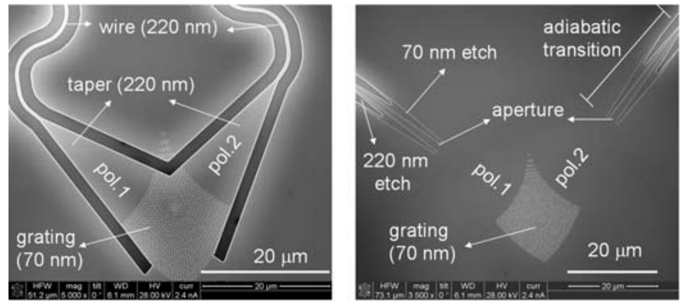


Figure 3. SEM-pictures of focusing 2D-grating couplers. (Left) Short non-adiabatic taper configuration. (Right) Shallow aperture configuration.

## IV. Measurements

We have measured the performance of the focusing grating couplers in two different configurations. In the first configuration, the light is focused onto a 500 nm wide photonic wire and the focusing wave is “guided” by a short-non adiabatic taper (Figure 3 left). In the second configuration, the light is focused onto a low lateral refractive index contrast aperture in order to reduce reflections at the interface. This aperture has an etch depth of 70 nm and the transition to high contrast waveguides is done adiabatically over 30 μm (Figure 3 right).

The performance of the grating couplers is analyzed through fiber-to-fiber transmission measurements. A fiber, connected with a tunable laser, is positioned over an input grating. At the output, light is coupled by a grating into another fiber connected with a photodetector. The measurement results are shown in Figure 4.

We consider two designs with different focal distances (determining the minimum q-value) corresponding with two different widths of the shallow aperture. In the first case, we use an aperture of 2.0 μm width. The focal distance is then 20.4 μm ($q_{min}$=36). The second design uses an aperture of 0.8 μm, corresponding to a focal distance of 11.9 μm ($q_{min}$=20). Both designs were also evaluated in short-taper configuration to a 500 nm photonic wire, where the taper length equals the above focal distances.

For the largest focal distance, short-taper and shallow aperture configuration perform equally well. The fiber to-fiber loss is 12 dB or 6 dB per grating coupler, which corresponds to a grating coupler efficiency of 25%. This is slightly better than standard 2D-grating couplers without focusing properties. The coupling efficiency can be further increased as described in [10, 11]. For the grating with the smallest focal distance, the shallow aperture configuration has 0.75-1dB higher fiber-to-fiber loss as compared to the short-taper configuration. In this case, the light cannot be focused to a spot as small as the aperture width (0.8 μm), while in the short taper configuration, the focusing wave is “guided” onto the photonic wire by the taper. The ripple on the transmission curves is higher in the shallow aperture case, indicating that there are still reflections. The grating with smallest focal distance in short-taper configuration has 0.5 dB excess loss

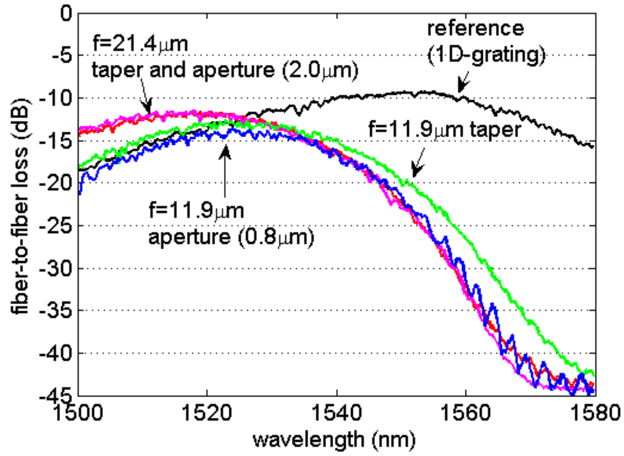

Figure 4. Fiber-to-fiber transmission for both configurations (short taper and shallow aperture) and different focal distances.

per coupler as compared to the grating with largest focal distance in short-taper configuration. In the first case, the taper is too steep to guide the light onto the photonic wire without some extra loss.

## V. POLARIZATION DEPENDENT LOSS

The focusing 2D-gratings can be used in a polarization diversity circuit. The polarization diversity circuit consists of input and output grating couplers and two connecting waveguide arms for each polarization. The Polarization Dependent Loss is measured again through fiber-to-fiber transmission measurements. The input polarization is changed randomly over all polarization states using polarization paddles, and the variation in transmission is measured at the output. The ratio between maximum and minimum transmission defines the Polarization Dependent Loss (PDL). We have measured a minimum fiber-to-fiber PDL of around 0.5 dB (Figure 5), which is as performant as standard non-focusing 2D-grating couplers. The PDL stays below 1 dB over a wavelength range of approximately 20 nm.

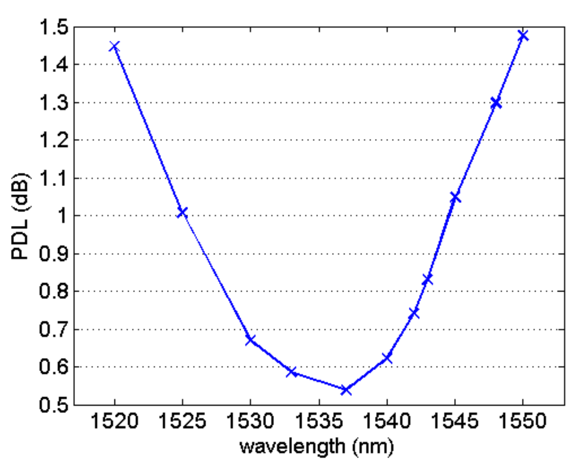

Figure 5. Measurement of the Polarization Dependent Loss.

## VI. CONCLUSIONS

We have demonstrated compact focusing 2D-grating couplers which can be used in a polarization diversity configuration. This way the coupling structure can be of dimensions of 20 μm (width) x 30 μm (length), which is an 8-fold reduction in length as compared to standard non-focusing versions. Both short non-adiabatic taper and shallow aperture configurations have been fabricated and analyzed, and no significant performance penalty has been observed. The Polarization Dependent Loss from fiber-to-fiber is measured to be 0.5 dB.

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