Focusing Polarization Diversity Grating Couplers in Silicon-on-Insulator

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***Abstract*—We report on compact focusing polarization diversity grating couplers in silicon-on-insulator, which can be used to overcome the polarization dependence of nanophotonic integrated circuits. The minimum fiber-to-fiber polarization dependent loss is 0.4 dB and the focusing grating couplers are as performant as standard 2-D-grating couplers without focusing. In addition, the focusing property of the gratings results in an 8-fold length reduction of the coupling structure as compared to standard nonfocusing 2-D-grating versions.**

***Index Terms*—Focusing grating, integrated optics, polarization diversity, silicon-on-insulator.**

I. Introduction

Silicon-on-insulator (SOI) is emerging as an interesting platform for high density integration of optical functions on a chip. The high refractive index contrast enables to make short bends, compact waveguides, etc. Several devices like cavities [1], demultiplexers [2], modulators [3], etc, have been demonstrated. Fabrication can be done by using mature technology from the CMOS industry.

However, making components smaller complicates the interfacing with the optical fiber, due to a mode mismatch between the fiber and the on-chip waveguides. Additionally, there is a polarization problem. The light from the fiber has an unknown polarization which also changes over time, while the nanophotonic components on the SOI-chip are often very polarization sensitive. Polarization diversity solves this problem in an elegant way and can be implemented using integrated polarization splitters and rotators on the chip [4], [5]. Another approach is using 2-D-grating couplers both for vertical fiber coupling and implementing polarization diversity without rather long polarization splitters and rotators [6]–[8]. As a consequence this approach can be far more compact and a much higher integration density can be achieved.

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So far, the size of the 2-D-grating coupler/polarization diversity structure was determined by an adiabatic transition ($>$ 150 μm) from a 12-μm–wide waveguide (i.e., the width of the grating, optimized for maximal overlap with the fiber mode) to 500-nm-wide single-mode photonic wires. However, by using curved gratings the light can be focused onto the photonic wire and the long adiabatic transition can be omitted, thus further increasing the integration density.

In previous work, we have shown first results on focusing grating couplers for SOI-waveguide circuits [9]. We described 1-D-focusing grating couplers (with periodicity in one direction) to substantially reduce the length of the coupling structure. However, these grating couplers are very polarization selective and do not solve the polarization problem. In this paper, we extend the principle to 2-D-grating couplers, which can be used in a polarization diversity configuration. This results in the same 8-fold length reduction (without performance penalty) and a measured fiber-to-fiber polarization dependent loss of only 0.4 dB. Furthermore, an experimentally verified analysis on focal distance and influence of the coupling angle is presented.

II. Design

The standard nonfocusing polarization diversity grating coupler consists of a rectangular lattice (12×12 μm^2) of holes and two (near) orthogonal waveguides. The grating can be considered as a superposition of two orthogonal standard 1-D-gratings, which are polarization selective [10]. As a consequence, each orthogonal polarization couples to its own (orthogonal) waveguide. In the waveguides the polarization is identical, i.e., TE, and they feed an identical polarization sensitive nanophotonic circuit. At the output, both arms are recombined with another grating coupler. In order to avoid reflections the fibers are tilted 10 degrees from vertical position. However, for symmetry reasons the fiber must then also be tilted along the bisection line of the grating, which increases the coupling to higher order modes due to a phase mismatch. In order to compensate for this mismatch the waveguides have to be rotated slightly. The waveguides for both polarizations are then not exactly orthogonal, but slightly tilted inwards. More details on standard nonfocusing 2-D-grating couplers and their use in polarization diversity circuits can be found in [6]–[8].

While rigorous design of the focusing 2-D-gratings would require computation-intensive 3-D-simulations, we have used simple equations for designing the gratings. We will compare their performance with standard nonfocusing 2-D-gratings to validate this approach. In analogy with standard 2-D-grating couplers, a focusing 2-D-grating coupler can also be understood as a superposition of two orthogonal focusing gratings. We have

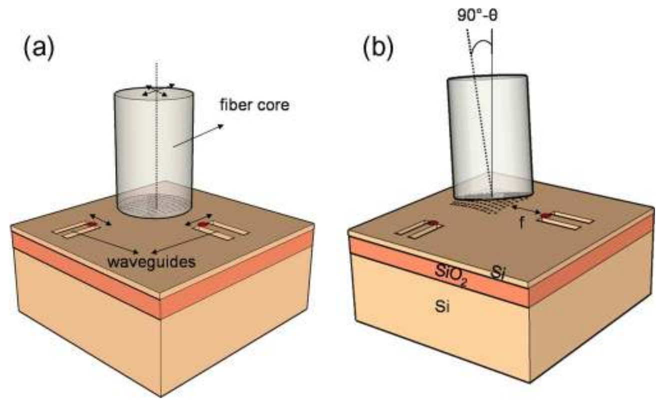

Fig. 1. (a) Vertical coupling. (b) Near-vertical coupling. In this case, the fiber is tilted along the bisection line of the grating.

made two different designs, based on the design of 1-D focusing grating couplers. In the case of a 1-D focusing grating the grating lines were obtained using following equation [11]:

$$q\lambda = n_{\text{eff}}\sqrt{y^2+z^2} - zn_{air}\cos(\theta)$$

where the focal point is at the origin, z is the coordinate in the propagation direction, y the coordinate in the lateral direction, q the grating line number, and θ the coupling angle. The right part of this formula is determined by the phase difference between the focusing (spherical) wave toward the photonic wire and the input wave from the fiber. For vertical coupling ($\theta = 90°$) the grating lines become concentric circles with the common center as the focus point. For near-vertical coupling (e.g $\theta = 80°$) the grating lines become ellipses with one common focal point. However, for small deviations from vertical coupling, the difference between circles (vertical coupling) and ellipses (near vertical coupling) is barely noticeable. The effective index n_{eff} is approximated by n_{eff} of the standard linear grating, determined by the Bragg condition for this grating. The wavelength is 1.55 μm. The focal distance f (determining the minimum q-number of the grating) 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. For the design of the focusing 2-D-gratings, we consider both vertical and near-vertical coupling (in order to avoid reflections), which are shown in Fig. 1.

A. *Design 1* ($\theta = 90°$)

Here, we use $\theta = 90°$ (i.e., vertical coupling) in the equation above. In this case, the 1-D-grating lines are circular. The 2-D focusing grating is formed by holes placed at the intersection of two overlaying orthogonal 1-D focusing gratings, obtained by applying the basic formula above. The overlay of two 1-D-focusing grating is shown in Fig. 2. One grating focuses on the point with coordinates $(y,z) = (0,0)$, while the other grating focuses on the point with coordinates $(y,z) = (-L,L)$. L is the distance from the focal point (0,0) to the center of the grating and is determined by the focal distance f and the number of grating lines (25 in this paper). The hole size is 380 nm, chosen the

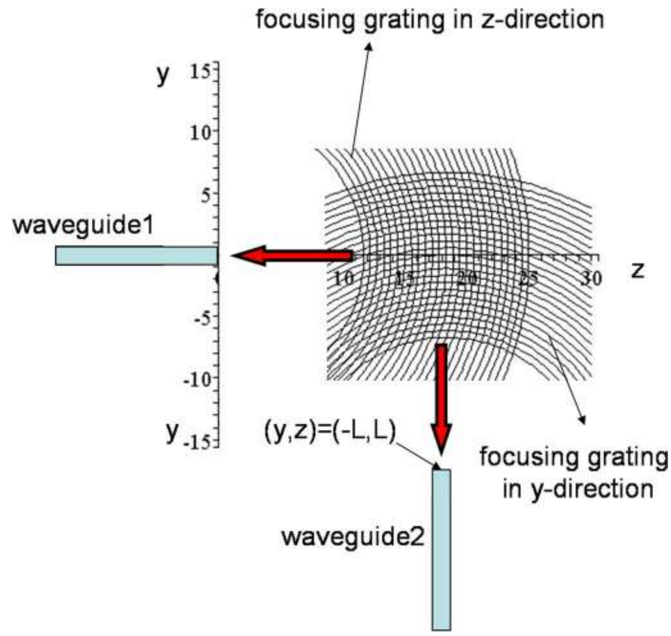

Fig. 2. Overlay of 2 orthogonal 1-D-focusing gratings. In order to obtain the 2-D-focusing grating, a hole is placed at the intersections of the overlaying gratings. Waveguides (orthogonal in this drawing) are indicated.

same as standard nonfocusing 2-D-gratings. Vertical coupling induces large second order reflection. In order to avoid this, we can still tilt the fiber (along the bisection line of the grating) but this has an influence on the coupling. First, the coupling spectrum blue shifts as compared to the vertical coupling case. In addition, a phase mismatch will occur, which can be compensated by rotating the waveguides, as was the case with standard nonfocusing grating couplers [8]. This will be verified experimentally.

B. *Design 2* ($\theta = 80°$)

Here we use $\theta = 80°$ and modify the phase relation for the input wave for coupling at an angle along the bisection line of the grating. The basic equation for the grating lines of a 1-D-grating with the focal point at the origin becomes

$$q\lambda = n_{\text{eff}}\sqrt{y^2+z^2} - (y+z)n_{air}\cos(\theta)\cos\left(\frac{\pi}{4}\right).$$

The output wave is still a spherical wave toward the photonic wire. Again we overlay two orthogonal 1-D focusing gratings, one with the focal point at coordinates $(y,z) = (0,0)$, the other with a focal point at coordinates $(y,z) = (-L,L)$. In this case, the waveguides do not need a rotation, since all phase relations are taken into account in the calculation of the grating.

III. Fabrication

The layer structure consists of a 220 nm top silicon layer on a 2 μm buried oxide layer on a silicon substrate. The patterns are fabricated using 193 nm deep UV lithography and ICP-RIE dry etching [12]. Samples were fabricated using two different etch depths, namely 70 nm (e.g., gratings) and 220 nm (e.g., photonic wires). Both require a separate patterning step, with

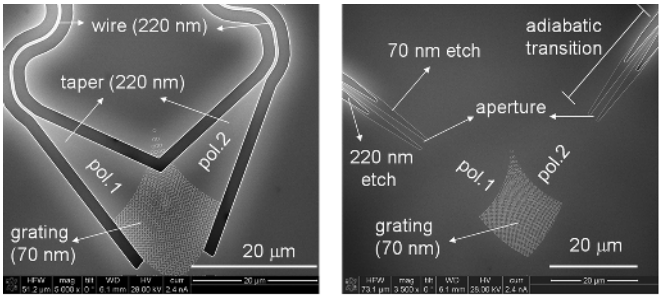

Fig. 3. SEM-pictures of focusing 2-D-grating couplers using a two-step etch process (70 and 220 nm depth). Left: short nonadiabatic taper configuration. Right: Shallow aperture configuration.

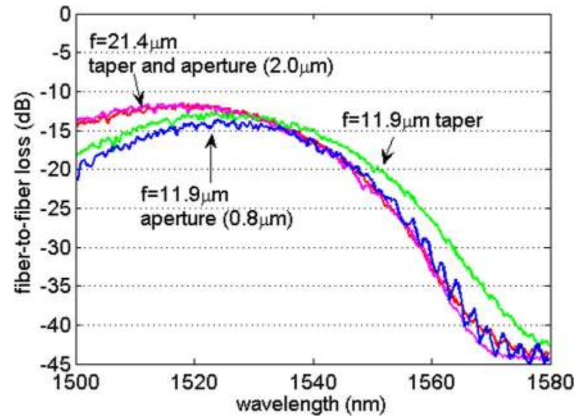

Fig. 4. Fiber-to-fiber transmission measurement for different focusing gratings in both short-taper and shallow aperture configuration. The reference curve is measured for standard 1-D-grating (nonfocusing). For the longest focal distance case, taper and aperture curves coincide.

an alignment accuracy of around 50 nm between both. SEM-Pictures of fabricated structures are shown in Fig. 3.

IV. Characterization

The structures are characterized through fiber-to-fiber transmission measurements. An input grating is used for coupling light from a tunable laser into the SOI waveguide circuit. The light is first coupled to a 500-nm-wide single-mode photonic wire as described below. The 500 nm wire is immediately tapered adiabatically to 800 nm width. At the output, the 800 nm waveguide is tapered down to 500 nm and the light is coupled into a fiber with an identical grating coupler and measured at a photodetector. Input and output coupler are spaced by 3 mm. The wires have a propagation loss of 2.4 dB/cm, resulting in an on-chip propagation loss of 0.8 dB.

A. Short Taper Versus Shallow Aperture

The different designs are evaluated for different configurations of the interface where the light is focused on. In a first approach, we use a focusing grating coupler in combination with a short taper to the single-mode photonic wire of 500 nm width (Fig. 3 left). In this case, the focusing wave is "guided" to the wire by the short taper. In a second approach, the light is focused in the slab onto a low lateral refractive index contrast aperture, having a shallow etch of 70 nm in order to reduce reflections at the interface (Fig. 3 right). An adiabatic transition of 30 μm length is used from low-contrast to high-contrast single-mode photonic wires (500 nm width). Fig. 4 shows measurement results for focusing 2-D-gratings based on design 2 $(\theta = 80^\circ)$. We made two different gratings with different focal distances (determining the minimum q-value of the grating lines) corresponding with two different shallow apertures. The focal distance for a 2.0 μm wide aperture is 21.4 μm $(\mathrm{q_{min}} = 36)$, while the focal distance for a 0.8 μm wide aperture is 11.9 μm $(\mathrm{q_{min}} = 20)$. For both gratings we also measured the performance for the short taper case where the taper length to the 500 nm photonic wire equals the above focal distances. Note that in all these measurements, we use angled coupling in combination with orthogonal waveguides.

For the grating with the largest focal distance, the shallow aperture (2.0 μm) and short taper configuration perform equally well. In this case, the fiber-to-fiber loss is -12 dB, of which 0.8 dB is propagation loss in the waveguides. The total coupling loss is -11.2 dB or -5.6 dB per grating coupler, corresponding with a coupling efficiency of 27%. This is slightly better than standard nonfocusing 2-D-couplers having a coupling efficiency of 21% (or coupling loss of -6.7 dB) [7]. The coupling efficiency can be further increased, as described in [13], [14]. For the grating with the smallest focal distance, the shallow aperture (0.8 μm) configuration has 0.75–1 dB higher fiber-to-fiber loss (or 0.37–0.5 dB per coupler) than the short-taper configuration. The reason is that the light cannot be focused to a spot as small as the aperture width (0.8 μm) resulting in excess loss, while in the short-taper configuration, the light is confined and "guided" towards the photonic wire by the taper. The ripple on the transmission curves is higher in the shallow aperture case especially for the small aperture, which indicates that there are still reflections at the interface. The grating with the shortest focal distance in short taper configuration has 0.5 dB excess loss per coupler as compared to the grating with longest focal distance, indicating that the "guiding" taper is too short in the first case.

B. Focal distance

In order to evaluate the design regarding the focal distance, we have varied the distance from grating to aperture or photonic wire around the value used in the calculations. We used again design 2 with calculated focal length of 21.4 μm $(\mathrm{q_{min}} = 36)$ and design 2 with calculated focal length of 11.9 μm $(\mathrm{q_{min}} =$ 20), both for shallow aperture and short taper configuration. We measured the transmission for defocus values of -10, -5, -2, 0, $+2$, $+5$ and $+10$ μm. The results are shown in Fig. 5.

For both cases, the optimal focus value is as calculated or slightly higher. In the longest focal distance design in short-taper configuration, a defocus of -5 μm results in 1 dB excess loss per coupler, while a positive defocus (i.e., taper longer than necessary) has nearly no influence on performance. The taper is in that case long enough to guide the light onto the wire, without extra loss. Note the high loss for a defocus of -10 μm (very steep taper). In the shallow aperture (2.0 μm) configuration, a defocus of -5.0 μm results in 1 dB excess loss per coupler and a defocus of $+10$ μm in 1.5 dB excess loss per coupler.

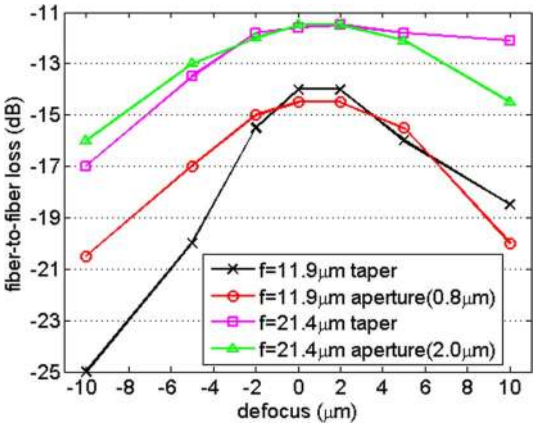

Fig. 5. Influence of defocus for both taper and shallow aperture configuration, for different focal distances.

In the shortest focal distance design in short-taper configuration, a defocus of -5 μm results in 3 dB excess loss per coupler, a positive defocus of 5 μm in 1 dB excess loss per coupler, and a 10 μm positive defocus in 2 dB excess loss per coupler. In this case, the taper is still too steep. Also, at the focal point the taper is wider than the focused spot, so its guiding effect is not fully exploited. For the 5 μm defocus, the taper is a bit steeper than for the 10 μm defocus case, but at the focal point the taper is narrower, so the guiding effect will be more exploited, explaining the higher transmission in this case. In the shallow aperture (0.8 μm) configuration, a defocus of -5.0 μm results in 1 dB excess loss per coupler, a positive defocus of 5.0 μm in 0.5 dB excess loss per coupler, and a defocus of $+10$ μm or -10 μm in 2.5 dB excess loss per coupler.

We can conclude that for negative defocus, the shallow aperture performs better than the taper configuration. For a positive defocus the "guiding" effect by the taper is efficient and the taper performs better in that case.

C. Influence of Waveguide Angle

We have fabricated both design 1 and design 2, with $q_{\min} = 20$, each time for 3 angles of the inward tilt ψ (Fig. 6) of the waveguides: 0 (i.e., orthogonal waveguides), 2 and 3.1 degrees. The angle $\psi = 3.1$ degrees was used since it is the optimal angle for standard nonfocusing 2-D-gratings in SOI with angled coupling, while 2 degrees is an intermediate value. In each measurement we use coupling at 10 degrees along the bisection line of the grating in order to avoid second order reflection (Fig. 1 right). Results are shown in Fig. 7.

For design1 (calculated for vertical coupling), this angled coupling results in a phase mismatch, which must be compensated by rotating the waveguides [Fig. 7(a)]. Also, by tilting the fiber the wavelength is blue shifted as compared to vertical coupling, which explains the shorter wavelength of the coupler spectrum. The angle giving best transmission is 3.1 degrees. A waveguide angle of 2 degrees results in an excess loss of 1 dB per coupling interface, which increases to 7.5 dB for orthogonal waveguides.

For design 2 (calculated for coupling at 10 degrees from vertical) the orthogonal waveguide case is optimal, since the phase relations are matched while designing the grating coupler [Fig. 7(b)]. A waveguide angle of 2 degrees results in an excess loss of 2 dB per coupling interface, which increases to 5.5–7.5 dB for a waveguide angle of 3.1 degrees.

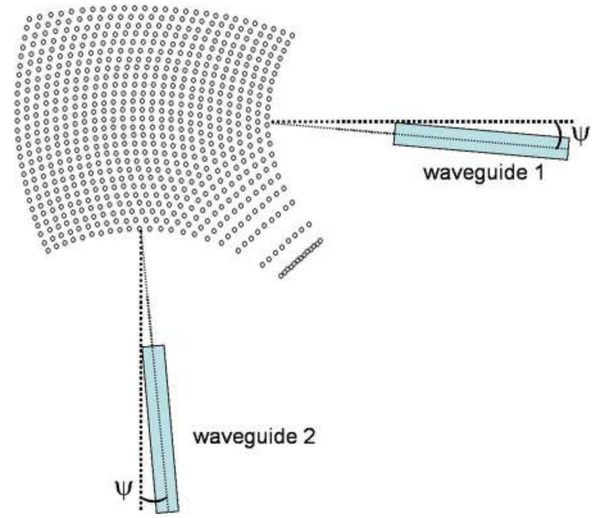

Fig. 6. Inward tilt ψ of the waveguides.

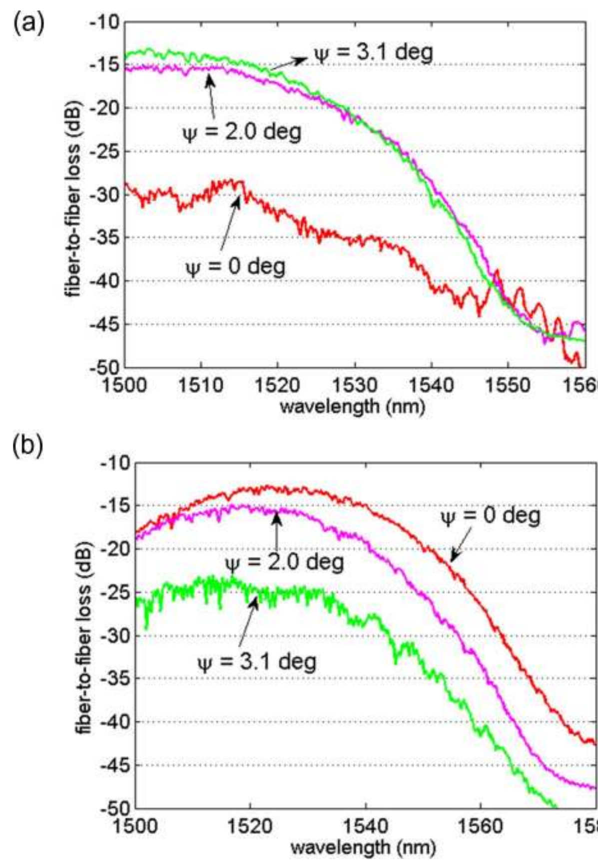

Fig. 7. Influence of angled coupling on the waveguide angle. (a) Design 1, which is calculated for vertical coupling, but measured for angled coupling. (b) Design 2, which is calculated and measured for angled coupling. The reference curves are measured for standard 1-D-grating (nonfocusing).

D. Polarization Dependent Loss

The focusing 2-D-gratings can be used in a polarization diversity circuit. The measured circuit consists of input and

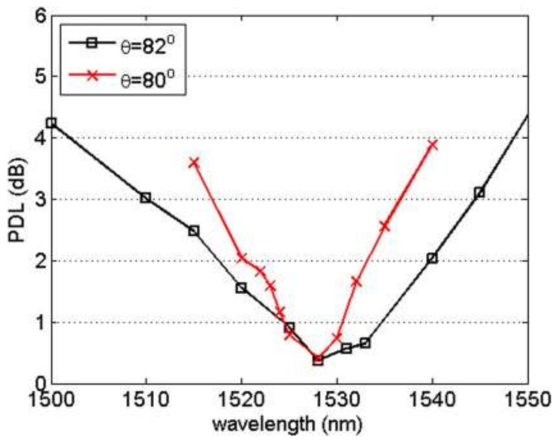

Fig. 8. Wavelength dependence of the fiber-to-fiber PDL.

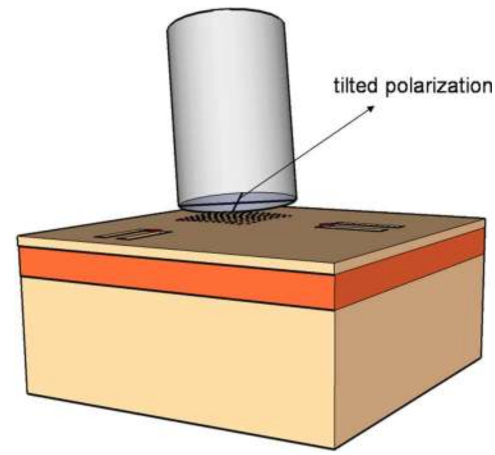

Fig. 9. Angled fiber coupling resulting in different coupling for orthogonal input polarizations along the bisection line of the grating.

output focusing gratings (design 2 with $\theta = 80°$, f $= 21.4\ \mu$m) connected by a waveguide circuit with two (orthogonal) arms. We have analyzed the performance by measuring the polarization dependent loss (PDL) from fiber-to-fiber. polarization mode dispersion (PMD) is not considered here. The PDL is measured by varying the polarization randomly over all possible states and calculating the ratio between minimum and maximum transmission

$$PDL(\text{dB}) = 10\log_{10}\left(\frac{T_{\max}}{T_{\min}}\right).$$

Due to the tilt of the fiber, the PDL is wavelength dependent, as shown in Fig. 8 for two angles of the fiber, $\theta = 80°$ and $\theta = 82°$, measured on the same grating. In the latter case the angle is different than the one used for calculating the grating, but the influence on the coupling efficiency is negligible. For each wavelength and at a fixed fiber position, the polarization is set for maximum and minimum transmission, from which the PDL is calculated. The minimum PDL value is 0.4 dB, which is lower than the PDL of 0.66 dB reported in [7], having, however, a more complex AWG-based circuit between input and output grating. Other reported realizations using polarization splitters and rotators show a PDL of around 1.0 dB [4], [5].

Here, the fiber-to-fiber PDL is low over a narrow wavelength range. From Fig. 8 it can be seen that the wavelength dependence of the PDL can be decreased by increasing the angle θ. However, vertical position and angles close to it can not be used due to reflections.

The wavelength dependence of the PDL can be explained by considering Fig. 9 and is already shortly described in [15].

By tilting the fiber, one of both orthogonal polarizations along the bisection line of the grating is tilted out of a plane parallel to the grating. Therefore, both polarizations do not experience the same grating, and the coupling efficiency of both polarizations is shifted in wavelength. Additionally, the optimal waveguide angle is not identical for both polarizations.

In Fig. 10 we show an experimental verification for both fiber angles $\theta = 80°$ and $\theta = 82°$. The wavelength is set to a value where the PDL is high (e.g., $\lambda = 1550$ nm for $\theta = 80°$) and the wavelength dependence of the transmission is measured for the two input polarizations where transmission is maximum and minimum at this wavelength. For $\theta = 80°$, a wavelength shift of 18 nm occurs between maximum and minimum transmission curves, while for $\theta = 82°$, the shift is reduced to 10 nm. This confirms the lower wavelength dependence for angles closer to vertical fiber position. At the wavelength where

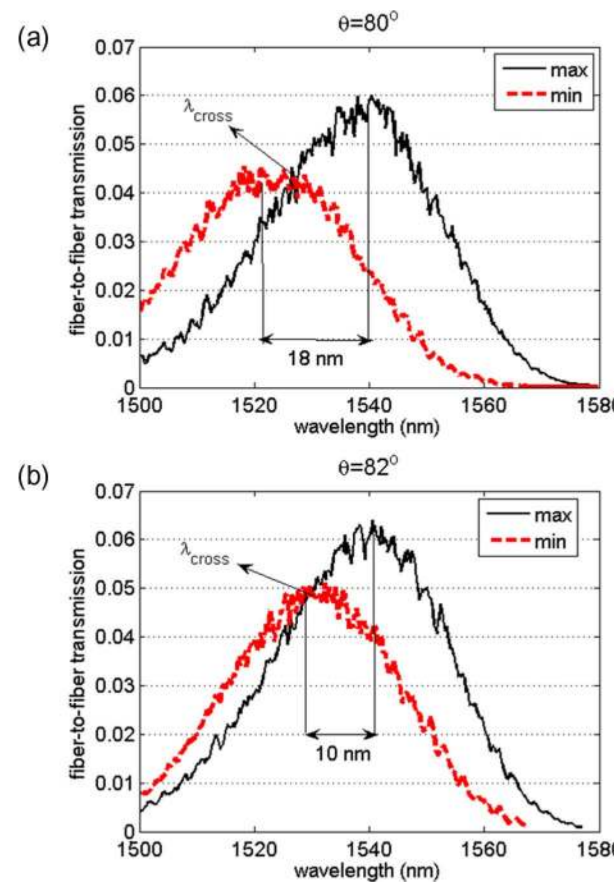

Fig. 10. Wavelength dependence of the transmission for polarizations giving maximum and minimum transmission. (a) $\theta = 80°$ (b) $\theta = 82°$.

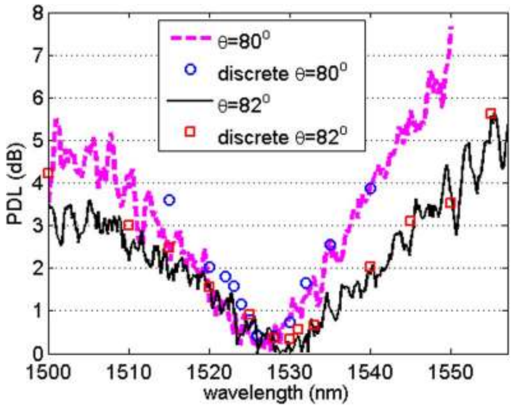

Fig. 11. Wavelength dependence of the PDL, obtained by the ratio between maximum and minimum transmission curves from Fig. 10. For comparison, discrete values from Fig. 8 are also added.

both curves intersect ($\lambda_{\rm cross}$) the PDL is zero in theory. For longer wavelengths, the ratio between maximum and minimum (and therefore PDL) increases rapidly, while for shorter wavelengths both curves lie closer to each other. In Fig. 11, we have taken the ratio between maximum and minimum transmission curves from Fig. 10 (continuous lines), together with the measured wavelength dependence of the PDL from Fig. 8 (discrete measurements points). A good correspondence between both is obtained.

However, in practice we do not measure zero but 0.4 dB PDL at the intersection wavelength ($\lambda_{\rm cross}$). The reason is that every deviation from perfect symmetry causes PDL. In the measured structure, asymmetry is caused by slight misalignment (fiber position, fiber angle) or slightly different propagation conditions in both waveguide arms. The PDL can be reduced by taking special care in fabricating identical waveguide arms and perfect alignment.

Fiber alignment tolerances of nonfocusing 2-D-polarization diversity grating couplers are theoretically described in [7], both in terms of PDL and coupling efficiency. A misalignment of $+/-1\mu$m results in 0.75 dB excess PDL and 0.5 dB excess coupling loss. Similar tolerances are expected for focusing 2-D-gratings.

V. Conclusion

We have designed, fabricated and analyzed focusing 2-D-grating couplers in SOI, which can be used in polarization diversity circuits. Both short transition from grating to photonic wire and focusing in the slab onto a shallow aperture were implemented. The short-taper configuration performs slightly better than the shallow aperture case if the aperture is small. The design of the gratings is based on a phase relation between incoming and outgoing wave and is tolerant to errors in focal distance. The fiber-to-fiber PDL is low (0.4 dB) over a narrow wavelength range. Future work will concentrate on eliminating the wavelength dependence of the PDL. The performance in terms of coupling efficiency (27%) is as good as or slightly better than standard nonfocusing 2-D-gratings. However, the focusing property results in an 8-fold length reduction of the coupling structure and hence a larger integration density. Thus, the size of SOI photonic integrated circuits is no longer determined by long adiabatic transitions between the coupling structure and the heart of the circuit.

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