Compact Focusing Grating Couplers for Silicon-on-Insulator Integrated Circuits

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***Abstract*—We report experimental results on compact and broadband focusing grating couplers, both in silicon-on-insulator (SOI) and gold on SOI. An eight-fold length reduction of the coupling structure from fiber to photonic wire in SOI, as compared to a linear grating and adiabatic taper, is obtained, without performance penalty. A proof of principle is given for a focusing grating coupler in gold on SOI, with 20% fiber-to-focus efficiency.**

***Index Terms*—Focusing grating coupler, gold, integrated optics, metal, nanophotonic waveguides, silicon-on-insulator (SOI).**

I. Introduction

THE high refractive index contrast of silicon-on-insulator (SOI) allows the creation of very dense photonic integrated circuits. However, the dimension reduction of the on-chip components has made coupling between these components and optical fibers non-trivial. An elegant edge-coupling method uses an inverse taper in combination with an overlay waveguide to adapt the mode of the photonic wire to the optical fiber mode (lensed or high numerical-aperture fiber) [1].

We use compact grating couplers, where a large periodic index change in an SOI waveguide enables broadband coupling by diffraction between the modes of a (near) vertically positioned standard single-mode fiber and the integrated waveguide. This approach has the prospect of wafer-scale testing. Typically these gratings measure 10 μm $\times$ 10 μm and are defined in a 10-μm-wide waveguide, which is then adiabatically tapered to a 500-nm-wide photonic wire, lengthening the structure with at least 150 μm. In [2], 33% coupling efficiency at a 1.55-μm wavelength, 40-nm 1-dB bandwidth and ± 2-μm alignment tolerance for 1-dB excess loss is experimentally shown for a grating obtained by periodically etching a SOI waveguide. An improved version by implementing a bottom reflector resulted in a measured coupling efficiency of 69% [3].

In [4], it is shown that an equivalent grating coupler can be obtained by depositing a periodic metal line pattern on top of the waveguide. For a gold grating on SOI, 34% efficiency at a 1.55-μm wavelength and a 35-nm 1-dB bandwidth is reported.

The adiabatic transition (typically longer than 150 μm) between wide (10 μm) and single-mode (500 nm) waveguide mainly determines the length of the coupling structure between fiber and chip. Focusing the light, which is diffracted by the grating onto the wire, would obviate the need for this long adiabatic transition. This would result in a substantial length decrease, and hence a higher degree of integration. Additionally, light could be focused directly on an integrated component, without needing a waveguide.

Focusing gratings have been studied for use in integrated-optic disk pickup devices [5]. In [6], weak (and, therefore, long) gratings were used for coupling light to waveguides on chip. Focal distances were of the order of a few millimeters. In [7], a holographic lens grating was briefly mentioned for coupling between fiber and SOI photonic wires, but no detailed results were reported yet.

Here, we elaborate the design and demonstrate focusing grating coupler structures both in SOI and gold on SOI. In SOI, a near vertical coupling structure with a 18.5 μm $\times$ 28 μm footprint between a standard fiber and a photonic wire is presented. This is an eight-fold length reduction as compared to a standard linear grating and adiabatic taper, without performance penalty. Additionally, a proof of principle is given for a gold focusing grating coupler, which acquires its full operation by a gold pattern on top of SOI, without taper or waveguide structure. It can be used to couple to a waveguide, but it also allows easy fabrication, and thus cheap, direct coupling to gold integrated components, e.g., a plasmonic circuit. Experiments show 20% fiber-to-focus efficiency.

II. Design Rules

In the case of the focusing grating couplers, efficient coupling is wanted between the transverse electric (TE) mode of an almost vertically positioned fiber, with a plain wavefront, and the TE modes of a broad SOI waveguide, so that the wavefront is curved cylindrically and focusing occurs in the center of curvature of the wavefront. When the top surface of the waveguide is chosen to be the (Y, Z) plane of a right handed Cartesian coordinate system, with z along the waveguide axis and the origin chosen to be in the desired focal point, it is shown in [6] that a

Manuscript received July 16, 2007; revised August 27, 2007. This work was supported in part by the European Union through the network of excellence ePIXnet. The work of F. Van Laere and S. Scheerlinck was supported by the Institute for the Promotion of Innovation through Science and Technology (IWT Flanders) under a scholarship. The work of W. Bogaerts was supported by the Fund for Scientific Research (FWO Flanders) under a post-doctoral grant. The work of D. Taillaert was supported by IWT Flanders under a post-doctoral grant.

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Digital Object Identifier 10.1109/LPT.2007.908762

focusing grating can be obtained by curving the grating lines as follows:

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

Here, q is an integer number for each grating line, θ_c is the angle between the fiber and the chip surface, n_t is the refractive index of the environment, λ_0 is the vacuum wavelength, and n_{eff} is the effective index felt by the cylindrical wave in the broad waveguide with the grating. The grating lines are ellipses with a common focal point, that coincides with the optical focal point of the coupler. The focal distance can be related to the minimal line number. While rigorous design of the focusing gratings would require full 3-D simulations, we approximate by extrapolating 2-D designs of standard linear gratings for TE-polarization (electric field parallel to the grating lines) and coupling at $\theta_c = 80°$. Near vertical coupling is used to avoid second-order reflection.

For the grating in SOI, the optimized design described in [2] is used, with a 630-nm period, 50% duty cycle and 70-nm etch depth, resulting in 37% theoretical efficiency at 1.55-μm wavelength. The focal distance (determining the minimal line number) is chosen as the distance where a spherical wave diffracting from the photonic wire, matches the dimensions of the fiber mode.

For the gold grating on SOI, finite-difference time-domain simulations have been used to optimize the linear grating. For SOI with 2-μm oxide, the optimal coupler for $\theta_c = 80°$, a central wavelength $\lambda_0 = 1.55$ μm and an air environment, was found to have a 590-nm period, 120-nm linewidth, and 20-nm lineheight. The theoretical efficiency is 32%. It is expected that higher efficiencies can be obtained by further optimizing the combination of coupling angle and SOI oxide thickness.

We directly applied the width and depth/height of the linear grating lines to the curved lines, and translated the period Λ to n_{eff} by using the projected Bragg-condition of the linear grating. We have neglected the fact that n_{eff} in the grating area differs from n_{eff} in the focusing area.

III. Focusing Gratings in SOI

A. Fabrication

The SOI-structures were fabricated using 248-nm-deep UV lithography and inductively coupled plasma–reactive ion etching (ICP-RIE) dry etching [8]. The gratings are etched to a depth of 70 nm into the top silicon layer. The waveguides and tapers are defined in a separate patterning step and etched through the top silicon layer (220 nm). Alignment accuracy between grating and waveguides is around 50 nm. In Fig. 1, top view scanning electron microscope pictures of the fabricated structures are shown.

B. Characterization

The performance of the couplers is determined from fiber-to-fiber transmission measurements, which are extensively described in [2]. A standard single-mode fiber, connected to a superluminescent light-emitting diode is positioned above

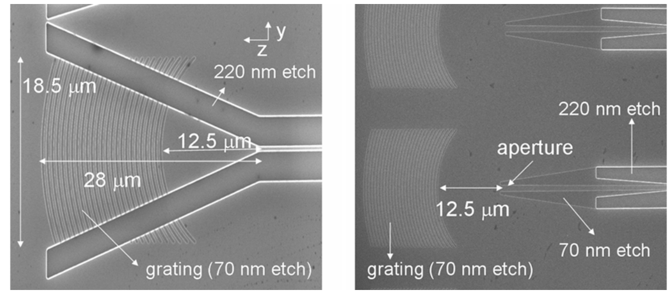

Fig. 1. (left) Focusing grating in SOI with a short taper (top view). (right) Focusing grating in SOI without taper, onto a low contrast aperture (top view).

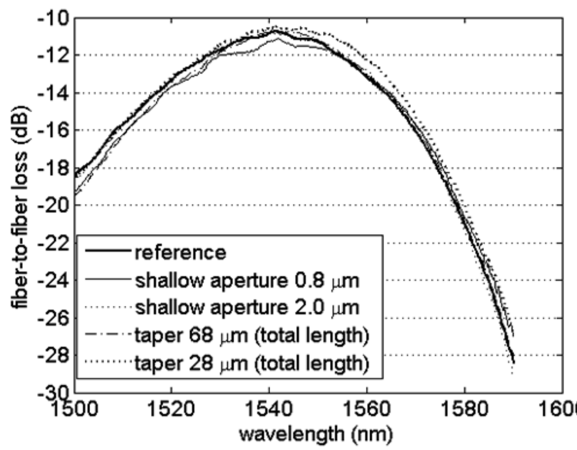

Fig. 2. Measurement results for focusing grating couplers in SOI in both configurations.

a focusing input grating (at 10° with respect to the vertical axis). Another fiber, connected to an optical spectrum analyzer is positioned (also at 10°) above a standard linear output grating with known efficiency. On the sample, we also have structures with two standard linear gratings (input and output) for referencing. In that case, a 700-μm-long adiabatic taper (with 100% theoretical transmission) is used between wide waveguide (10 μm) and single-mode wire (500 nm).

We have measured focusing grating couplers in the two different configurations shown in Fig. 1. In Fig. 1 (left), we use a focusing grating in combination with a short, linear, nonadiabatic taper to a 500-nm wire. In Fig. 1 (right), the light is focused by the grating onto a low contrast aperture ranging from 0.8 to 2 μm. This low-contrast aperture was implemented in a 70-nm etch (instead of a full etch) using the same two-step etch process used to define the gratings. The lower lateral index contrast reduces reflections at the aperture. The transition from low-contrast to high-contrast waveguides is done adiabatically over a 30-μm length.

The measurements are shown in Fig. 2. In the short-taper configuration, the focusing grating couplers perform equally well to the reference linear gratings. The fiber-to-fiber loss is 10.5 dB, corresponding with a coupling efficiency of a single grating coupler around 30%. The most compact structure of this type has a total footprint of 18.5 μm (width of the grating) by 28 μm (grating + taper). In the shallow-aperture configuration, the fiber-to-fiber loss increases slightly by 0.6 dB for the narrowest (0.8 μm) aperture. The dimensions of the coupling

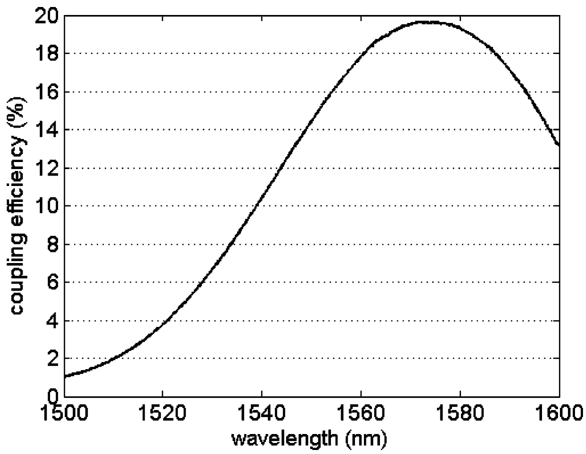

Fig. 3. Measurement of the fiber-to-focus coupling efficiency of a gold focusing grating on SOI, with parameters as described in Section IV-A. The focal distance was designed to be 125 μm.

structure to the aperture are 18.5 μm (width of the grating) by 30 μm [grating length + free propagation region (12.5 μm)]. Wider apertures show no performance penalty.

IV. Gold Focusing Grating Couplers

A. Fabrication

The devices were fabricated through the ePIXnet Nanostructuring Platform for Photonic Integration,[1] using a combination of electron beam lithography and gold lift-off. On blank SOI with 2-μm oxide and 220-nm Si, 20 gold lines were created with 119-nm width and 20-nm height. The effective index was chosen to be 2.7787, which corresponds to a 595-nm period in the middle of the grating. No waveguides were defined, so the top silicon layer will only confine the light in the vertical direction.

B. Characterization

The fabricated couplers are organized in pairs of identical gratings with mutual focal points, so that the power coupled from a fiber to the chip by one coupler will be captured by the other, and coupled to a second fiber. The fibers were positioned at 10° to the vertical axis. In order to separate the in and out coupling fiber enough, the minimal focal distance of the fabricated gratings was 125 μm. By taking the square root of the measured fiber-to-fiber efficiency, a lower bound of the fiber-to-focus efficiency can be calculated, assuming perfect focusing and no propagation losses. Fig. 3 shows 20% efficiency at $\lambda_0 = 1575$ nm for a grating with 125-μm focal distance. The 1-dB bandwidth is 41 nm. Fig. 4 illustrates what happens to the efficiency when gratings with 250-μm focal distance are relatively shifted in the longitudinal direction, causing the focal points of the in and out coupling gratings to be at different positions (according to the design). When the focal points coincide, the efficiency was measured to be low, which is probably caused by a damaged coupler. This coupler is located far from the other

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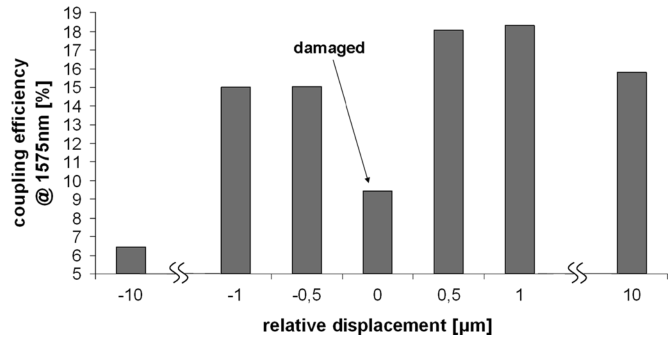

Fig. 4. Influence of a relative longitudinal shift of gratings with 250-μm focal distance. The shift is negative when the gratings are positioned closer to each other and positive otherwise.

ones, suggesting other fabrication conditions. The other measurements show that the efficiency at first increases when the couplers are separated more, both proving that the gratings focus and that the real focal distance of the gratings is larger than designed. This is caused by neglecting the fact that the effective index in the focusing area is larger than the one in the grating area when designing the gratings. It is, however, expected that the influence of this aberration will decrease with decreasing focal distance.

V. Conclusion

Experimental results of compact and broadband focusing grating couplers, both in SOI and gold on SOI, were presented. It was shown that an eight-fold length reduction of the coupling structure from fiber to photonic wire in SOI, as compared to a linear grating and adiabatic taper, can be obtained by curving the grating lines, without performance penalty. Measurements indicated that a focusing grating coupler can also be obtained by defining a gold pattern on top of SOI.

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