Vertical fiber-to-waveguide coupling using adapted fibers with an angled facet fabricated by a simple molding technique

Stijn Scheerlinck,* Jonathan Schrauwen, Gunther Roelkens, Dries Van Thourhout, and Roel Baets

IMEC-Ghent University, Photonics Research Group, Sint-Pietersnieuwstraat 41, 9000 Gent, Belgium

*Corresponding author: stijn.scheerlinck@intec.ugent.be

Received 8 February 2008; accepted 7 May 2008;
posted 30 May 2008 (Doc. ID 92601); published 11 June 2008

Vertical coupling between silicon-on-insulator waveguides and optical fibers is achieved using adapted fibers with an angled facet. The proposed coupling scheme is demonstrated for waveguides containing uniform one-dimensional grating couplers. A coupling efficiency of 32% and a 1 dB bandwidth of 32 nm are measured at a wavelength of 1550 nm. We demonstrate single-step fabrication of these fibers using a simple molding technique.

OCIS codes: 130.0130, 050.2770.

1. Introduction

Silicon-on-insulator (SOI) technology is emerging as a promising platform for integrated optics due to the high refractive index contrast between the silicon core and the oxide cladding ($\Delta n \approx 2$). This enables high-density integrated optical circuits, which can be fabricated using standard complementary metal-oxide semiconductor (CMOS) technology including deep ultraviolet (DUV) lithography [1]. One of the drawbacks of the high index contrast is the large mismatch in mode size between the fundamental mode of the SOI waveguide and the mode of the optical fiber, making efficient coupling of light between waveguides and fibers an important issue. Grating couplers are an elegant solution for the coupling problem [2,3]. Compact one-dimensional [4] and two-dimensional [5] grating structures, as well as focusing grating structures [6], have been developed for the SOI material platform. These grating couplers are very compact—typically $10\,\mu\text{m} \times 10\,\mu\text{m}$—and have the advantage of not having to cleave the devices for optical coupling. This enables wafer-scale testing of the integrated circuits and holds the promise of low-cost packaging. Given that one-dimensional structures are highly polarization dependent, a polarization diversity scheme based on a two-dimensional grating coupler can be used in practical applications [5]. Simple uniform gratings are the most easy to fabricate. Over 30% coupling efficiency has been demonstrated for these couplers and 69% has been obtained by including a bottom mirror [7]. More elaborate nonuniform and asymmetric grating designs have been proposed and promise even higher coupling efficiencies [8,9]. All of these grating couplers have in common that the grating is designed in such a way that optimal coupling occurs when the optical fiber is slightly tilted with respect to the vertical axis, typically 10° off the vertical. This is necessary to avoid a large second order Bragg reflection back into the waveguide. Such reflections might deteriorate the optical performance of the integrated circuit and also reduce the coupling efficiency. However, the requirement of slightly tilting the fiber compromises the applicability of these grating couplers for testing and packaging purposes. A coupling scheme in which the fiber is in a perfectly vertical position with respect to the waveguide plane is much more attractive. It drastically facilitates fiber mounting and thus keeps packaging costs low, especially when it

---

0003-6935/08/183241-05$15.00/0

comes to mounting of one- or two-dimensional fiber arrays. Vertically positioned fibers are also more advantageous for wafer-scale testing schemes with multiple fibers as the individual space volume needed for testing is minimal. This understanding has led to novel grating designs that incorporate extra slits in the waveguide layer that act as a mirror in order to achieve destructive interference of these reflections [10]. Slanted grating couplers based on angled slits are another solution [11]. However, the fabrication of these types of grating couplers is extremely challenging. In this paper, we propose an alternative solution for vertical fiber-to-waveguide coupling without second order Bragg reflections. This alternative solution relies on the conventional grating coupler design with optimal coupling into the slight off-vertical direction and a vertically positioned optical fiber with an angled facet. The principle of the proposed coupling scheme is illustrated in Fig. 1(a) and is based on a fiber with an angled facet in a perfectly vertical position with respect to the waveguide plane. We propose and demonstrate the definition of the angled facet using a simple single-step molding process of a UV-curable polymer. This process is easily expandable to multiple fibers at a time. With this technique, delicate mechanical angle polishing of fibers is avoided. We will use these fibers to experimentally demonstrate vertical fiber-to-waveguide coupling with conventional SOI grating couplers.

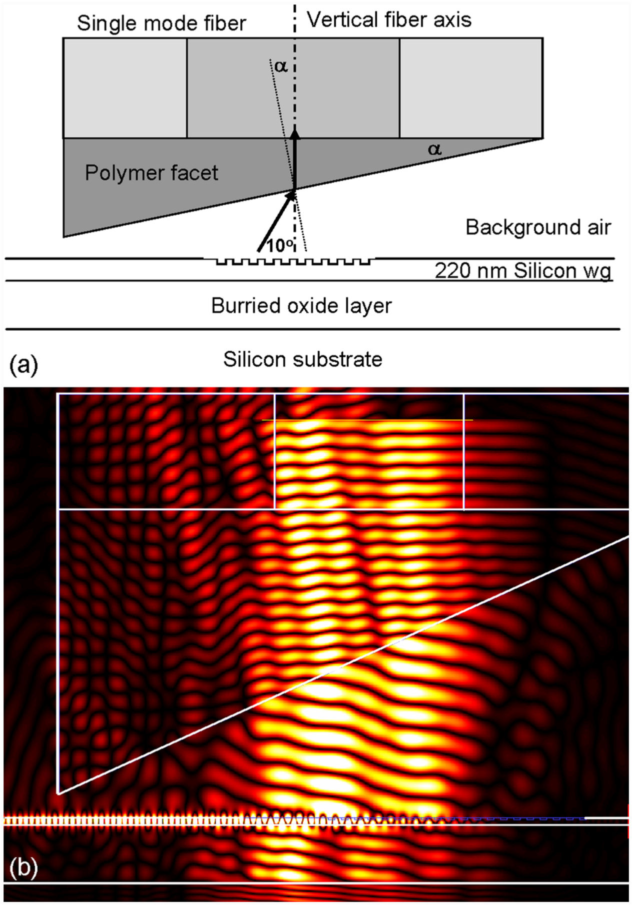

Fig. 1. (Color online) (a) Proposed coupling scheme between an SOI waveguide and a perfectly vertical optical fiber using a conventional grating coupler and an adapted single-mode fiber with an angled facet. The grating coupler is designed for near-to-vertical diffraction by 10° off the vertical axis to avoid secondary order reflections back into the waveguide. The angled polymer facet causes refraction into the vertically positioned single-mode fiber. (b) FDTD simulation of the coupling scheme illustrates the refraction of the outcoupled light into the fiber.

2. Design

The design of the adapted fiber is based on Snell's law. Conventional SOI grating couplers are designed such that light with a wavelength of 1550 nm and guided by the top silicon waveguide layer is optimally diffracted in a direction which is 10° off the vertical axis. By introducing an interface between the background air and a higher refractive index polymer, the outcoupled light will be refracted. Depending on the refractive index of the polymer medium, the angle of the interface with respect to the vertical can be chosen so that the light is refracted into the vertical direction. This angle can be calculated from the scheme in Fig. 1 using Snell's law which transforms into the following equation:

$$n_1 \sin \alpha = n_0 \sin(\alpha + 10°), \tag{1}$$

with n_0 the refractive index of the background air and n_1 the refractive index of the high index medium. The refractive index of the UV-curable polymer is 1.506 at a wavelength of 1545 nm, which is the value taken for the calculation. For air, a refractive index of 1 is taken. With these parameters, an angle $\alpha = 18°$ follows from Eq. (1). Simulation of this coupling scheme using an 18° polymeric facet on a single-mode fiber with 2-dimensional finite difference time domain (FDTD) calculations (Omnisim 4.0, Photon Design) confirms the refraction of the outcoupled light into the vertically positioned fiber. This is illustrated by the field plot in Fig. 1(b). The simulated structure consists of an SOI waveguide (220 nm top silicon layer of refractive index 3.476 on top of a 2 μm oxide layer of refractive index 1.45) containing a standard grating coupler with a period of 610 nm, a filling factor of 50%, and an etch depth of 70 nm. The single-mode fiber consists of a 10.4 μm diameter core of refractive index 1.46 surrounded by a cladding of refractive index 1.455. From these calculations a waveguide-to-fiber output coupling efficiency of 44% is calculated. In the experimental part of this paper, we will compare the theoretical results with our experimental results. At this point, we note that the fiber-to-waveguide input coupling efficiency and the waveguide-to-fiber output coupling efficiency are equal. The reason is that we use single-mode fibers and coupling to and from the fundamental waveguide mode. The system is therefore reciprocal and the reciprocity theorem is valid [12,13]. It follows that the transmission from the fiber mode to the waveguide mode and from the waveguide mode to the fiber mode are the same.

3. Fabrication

The proposed single-step fabrication process flow is depicted in Fig. 2 and was carried out in the following way. The starting point was a straight-cleaved single-mode fiber and a specially prepared silicon sample. First, the silicon sample was treated to obtain an antiadhesion layer. For this purpose, the sample was treated with (tridecafluoro-1,1,2,2-tetrahydrooctyl)trichlorosilane ($C_8H_4Cl_3F_{13}Si$, ABCR GmbH) in a pentane solution (0.1%) and subsequent rinsing using acetone, isopropyl alcohol, and water. The sample was then fixed on a vacuum chuck and the fiber was mounted on an x, y, z-stage using a fiber holder which makes an angle of 18° with respect to the vertical. The fiber end was then immersed for a few seconds in a drop of UV-curable resist (PAK-01, Toyo Gosei Co.) to cover the facet of the fiber. Next, the fiber was brought close to the antiadhesion treated silicon surface, thereby shaping the liquid resist by squeezing it between the fiber facet and the silicon surface. The resist was then cured by UV-light from an EFOS Ultracure 100 ss-plus system by illuminating the fiber end for 5 min. Doing so, the shape of the polymer at the fiber end got fixed. In a final step, the fiber was lifted from the silicon sample with the fabricated polymer wedge attached to it. Because of the antiadhesion layer on the silicon sample, no adhesion occurred between the silicon sample and the polymer. The result is a fiber containing a polymeric facet termination that makes an angle of 18° with respect to the original fiber facet. Figure 3 depicts a picture of the device taken with scanning electron microscopy (SEM).

4. Experimental Results

Coupling from a perfectly vertical optical fiber to a single-mode SOI photonic wire and back into a second perfectly vertical fiber was demonstrated experimentally. The $220\,\text{nm} \times 500\,\text{nm}$ photonic wire was connected via tapers between two $10\,\mu\text{m}$ broad access waveguides containing standard grating couplers with 630 nm period and 70 nm etch depth. The SOI layer stack consisted of a 220 nm top silicon layer and a $2\,\mu\text{m}$ buried oxide layer. The two fibers were adapted and provided with the polymeric angled facet using the procedure described above. The first fiber was connected to a broadband superluminescent light-emitting diode (SLED) source with an output power of 10 mW and a central wavelength of 1535 nm. The second fiber was connected to a spectrum analyzer with a built-in power monitor. A schematic of the experimental setup and a top view schematic of the SOI waveguide structure are depicted in Fig. 4. After a passive alignment procedure using a camera, an active alignment procedure was carried out to optimize the position of the fibers by monitoring the fiber-to-fiber power transmission at a wavelength of 1550 nm. Polarization wheels were used to control polarization. Given that the input and output coupling efficiency are the same in theory, the fiber-to-waveguide coupling efficiency can be extracted from the measurements by subtracting—on a logarithmic scale—the measured spectrum from the source spectrum and dividing by a factor of 2. From this measurement, a fiber-to-waveguide coupling efficiency of 32% and a 1 dB bandwidth of 32 nm were extracted. The spectral dependence is plotted in Fig. 5. For comparison, the experiment was repeated with two straight-cleaved fibers. The fiber-to-waveguide coupling efficiency was extracted in the same way and was included in the graph. The coupling efficiency is very low, illustrating the necessity of the angled facet when coupling between perfectly vertical optical fibers and waveguides containing these grating couplers. There is a slight discrepancy between the simulated and measured coupling spectrum: the difference in coupling efficiency is about 1 dB and there is a slight shift in wavelength. This can be explained as follows. First of all, previous work has shown that the measured coupling efficiency of SOI grating couplers is always lower by about 0.7 dB than theoretically expected and that slight wavelength shifts in the order of 10 nm can be attributed to fabrication errors [4]. Furthermore, the distance between the grating and the actual fiber facet was limited in the simulations to $6\,\mu\text{m}$ for saving calculation time, whereas it is about $40\,\mu\text{m}$ in the

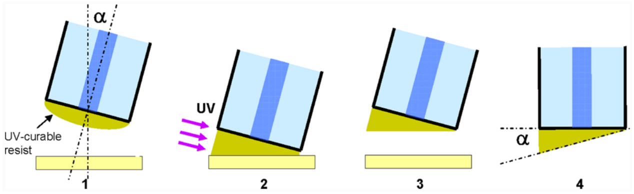

Fig. 2. (Color online) Single-step fabrication of an optical fiber with an angled polymer facet. (1) The process starts from a straight-cleaved fiber tilted by the desired facet angle with respect to the vertical and a silicon sample treated with an antiadhesion layer, (2) UV-curable resist is squeezed between the fiber facet and the silicon sample, (3) release of the fiber. (4) The facet angle equals the initial fiber axis tilt.

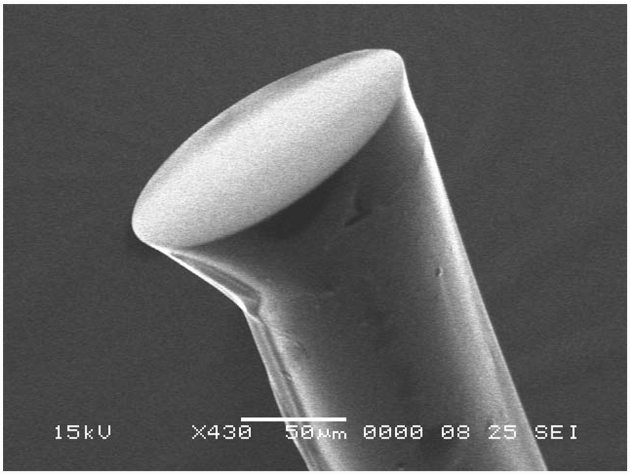

Fig. 3. SEM picture of the fabricated angled facet fiber.

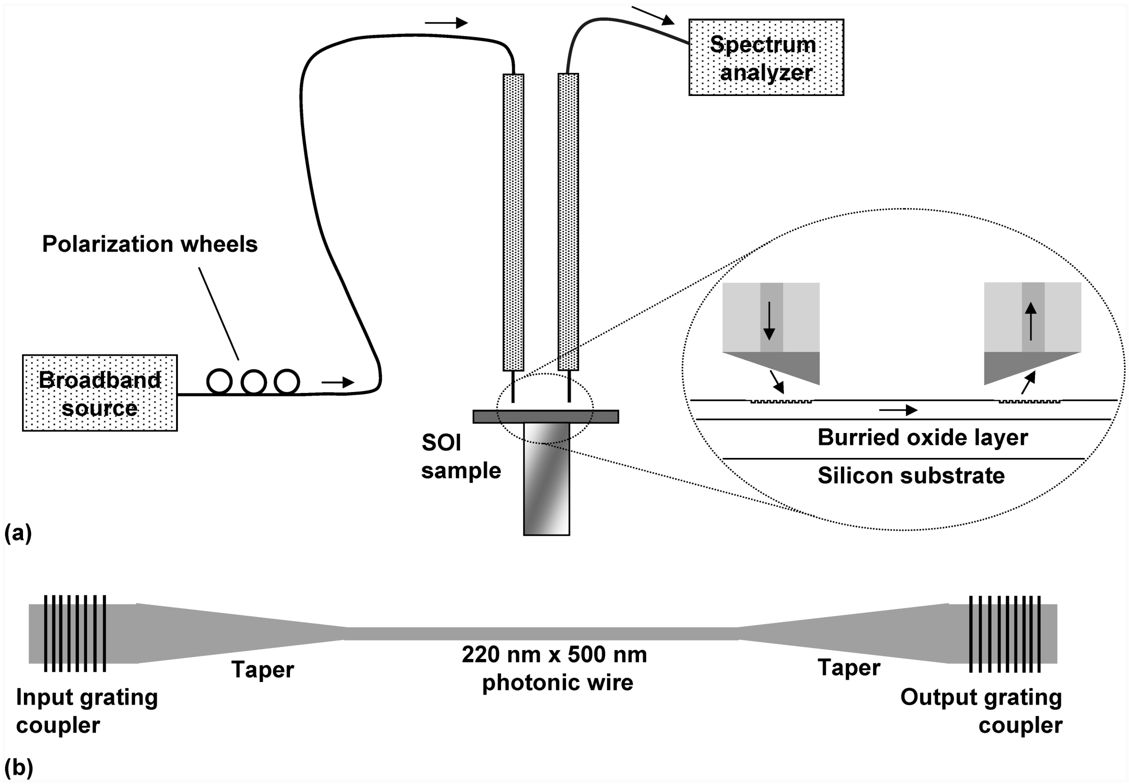

Fig. 4. (a) Schematic of the experimental setup. The input fiber is connected to a broadband superluminescent source via polarization wheels to control the polarization. The output fiber is connected to a spectrum analyzer. An angled facet is fabricated on both fibers. The arrows in the figure show the light path through the setup. As shown in the inset, light is refracted by the angled facet and coupled in and out of the top silicon waveguide layer of the SOI sample via grating couplers. (b) Top view schematic of the silicon waveguide structure containing input and output grating couplers for coupling to a photonic wire via taper structures.

measurements. This accounts for an additional loss of 0.4 dB. We conclude that there is good agreement between the simulation and the experiment for the proposed coupling scheme.

5. Conclusion

A novel coupling scheme for perfectly vertical fiber-to-waveguide coupling was presented based on adapted fibers with an angled facet and conventional grating couplers. The angle of the facet was calculated from Snell's law and confirmed by FDTD calculations. A simple single-step process was proposed to fabricate these fibers. Coupling between an SOI waveguide and two perfectly vertical optical fibers was demonstrated with a fiber-to-waveguide coupling efficiency of 32% and a 1 dB bandwidth of 32 nm. This is a 15 dB increase when compared to perfectly vertical coupling using straight-cleaved fibers. The experimental results are in good agreement with our simulations.

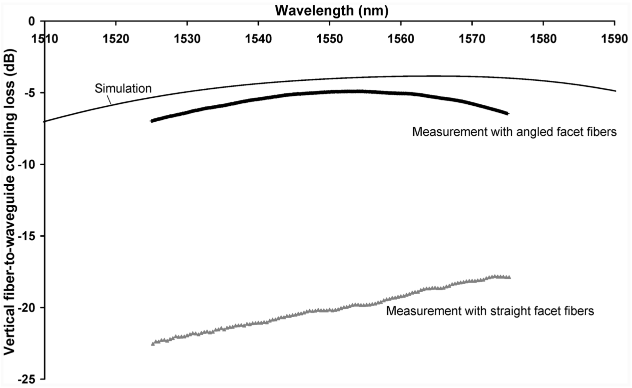

Fig. 5. Experimentally determined fiber-to-waveguide coupling spectrum extracted from a fiber-to-fiber measurement with two vertically positioned adapted fibers with and without an angled facet. The theoretical curve for the angled facet fibers is also plotted.

This work was partly supported by the European Union through the Network of Excellence ePIXnet, by the Belgian IAP-PHOTON Network, and by Ghent University through the GOA biosensor project. S. Scheerlinck thanks the Institute for the Promotion of Innovation through Science and Technology in Flanders (IWT-Vlaanderen) for a scholarship. The authors thank Toyo Gosei for kindly providing PAK-01.

References

1. W. Bogaerts, R. Baets, P. Dumon, V. Wiaux, S. Beckx, D. Taillaert, B. Luyssaert, J. Van Campenhout, P. Bienstman, and D. Van Thourhout, "Nanophotonic waveguides in silicon-on-insulator fabricated with CMOS technology," J. Lightwave Technol. **23**, 401 (2005).

2. T. Suhara and H. Hishihara, "Integrated optics components and devices using periodic structures," IEEE J. Quantum Electron. **22**, 845 (1986).
3. R. Orobtchouk, A. Layadi, H. Gualous, D. Pascal, A. Koster, and S. Laval, "High-efficiency light coupling in a submicrometric silicon-on-insulator waveguide," Appl. Opt. **39**, 5773 (2000).
4. D. Taillaert, F. Van Laere, M. Ayre, W. Bogaerts, D. Van Thourhout, P. Bienstman, and R. Baets, "Grating couplers for coupling between optical fibers and nanophotonic waveguides," Jpn. J. Appl. Phys. **45**, 6071 (2006).
5. D. Taillaert, H. Chong, P. I. Borel, L. H. Frandsen, R. M. De La Rue, and R. Baets, "A compact two-dimensional grating coupler used as a polarization splitter," IEEE Photon. Technol. Lett. **15** 1249 (2003).
6. F. Van Laere, T. Claes, J. Schrauwen, S. Scheerlinck, W. Bogaerts, D. Taillaert, L. O'Faolain, D. Van Thourhout, and R. Baets, "Compact focusing grating couplers for silicon-on-insulator integrated circuits," IEEE Photon. Technol. Lett. **19**, 1919 (2007).
7. F. Van Laere, G. Roelkens, J. Schrauwen, D. Taillaert, P. Dumon, W. Bogaerts, D. Van Thourhout, and R. Baets, "Compact and highly efficient grating couplers between optical fiber and nanophotonic waveguides in bonded InP-membranes," in *IEEE Conference on Optical Fiber Communications (OFC)* (Optical Society of America, 2006), paper PDP15.
8. D. Taillaert, P. Bienstman, and R. Baets, "Compact efficient broadband grating coupler for silicon-on-insulator waveguides," Opt. Lett. **29**, 2749 (2004).
9. G. Roelkens, D. Van Thourhout, R. Baets, R. Noetzel, and M. Smit, "High efficiency silicon-on-insulator grating coupler based on a poly-silicon overlay," Opt. Express **14**, 11622 (2006).
10. G. Roelkens, D. Van Thourhout, and R. Baets, "High efficiency grating couplers between silicon-on-insulator waveguides and perfectly vertical optical fibers," Opt. Lett. **32**, 1495 (2007).
11. B. Wang, J. H. Jiang, and G. P. Nordin, "Embedded slanted grating for vertical coupling between fibers and silicon-on-insulator planar waveguides," IEEE Photon. Technol. Lett. **17**, 1884 (2005).
12. R. Harrington, *Time-Harmonic Electromagnetic Fields* (McGraw-Hill, 1961).
13. F. Olyslager, *Electromagnetic Waveguides and Transmission Lines* (Oxford Univ., 1999).